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Wet Scrubber System Study

Vol. 2 final report and bibliography

A.P.T., Inc.

prepared for
Environmental Protection Agency

JULY 1972

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WET SCRUBBER SYSTEM STUDY

Volume I.

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July 1972

FINAL REPORT and BIBLIOGRAPHY

Prepared For
ENVIRONMENTAL PROTECTION AGENCY
Control Systems Division

July 1972

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The study was undertaken to achieve the following objectives: (1) Evaluate current engineering technology, (2) Evaluate existing scrubber systems, (3) Investigate present usage problems, (4) Determine potential new applications, (5) Develop specific research recommendations. The approach and method used to achieve the objectives are described. Two R & D plans are presented; one at a $2 million, five-year level, and the second at a $7 million five-year level. The Bibliography contains about 1,700 references discussing various aspects of wet scrubbers.

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WET SCRUBBER SYSTEM STUDY VOLUME II

FINAL REPORT

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David Leith
Dilip Mehta

Prepared for

CONTROL SYSTEMS DIVISION
OFFICE OF AIR PROGRAMS - ENVIRONMENTAL PROTECTION AGENCY

CONTRACT NO. CPA-70-95

A.P.T., INC.
(Ambient Purification Technology)
P. O. Box 71, Riverside, California 92502

July, 1972

Ib

FORWARD

The Final Report and Bibliography is Vol. II of a two-volume report submitted to the Office of Air Programs - Environmental Protection Agency, as part of the Wet Scrubber System Study under Contract No. CPA-70-95. The first volume is entitled Scrubber Handbook. The two volumes are available from NTIS.

The principal objectives of this study were: (1) To evaluate the current engineering technology, (2) To evaluate existing scrubber systems, (3) To investigate present usage problems, (4) To determine potential new applications, and (5) To develop specific research recommendations.

Mr. Dale Harmon of the Control System Division, Office of Air Programs, served as the contract project officer through most of the contract. He was later replaced by Dr. Leslie Sparks of the same division.

ENVIRONMENTAL PROTECTION AGENCY REVIEW NOTICE

This report has been reviewed by EPA and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of EPA, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

A Wet Scrubber System Study was undertaken to achieve the following objectives: (1) Evaluate current engineering technology, (2) Evaluate existing scrubber systems, (3) Investigate present usage problems, (4) Determine potential new applications, (5) Develop specific research recommendations. The products of this study are: (1) Scrubber Handbook, (2) Final Report, (3) Bibliography, (4) R & D Plan. The Scrubber Handbook brings together previously scattered material and makes clear its applicability to scrubber technology. It discusses the various aspects of scrubber use and present engineering design methods based on a unifying concept. Actual experience on hundreds of scrubber installations is presented in a condensed form. Many related topics such as auxiliaries, materials of construction, physical and chemical data, cost estimation and optimization techniques, and the disposal of liquid and solid wastes are all covered thoroughly in the Scrubber Handbook.

The Final Report and Bibliography describes the approach and method used to achieve the objecties listed earlier. It presents two R & D plans; one at a $2 million, five-year level, and the second at a $7 million five-year level. The Bibliography contains about 1,700 references discussing various aspects of wet scrubbers.

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SUMMARY

A.P.T. conducted a Wet Scrubber System Study under Contract CPA-70-95 with EPA/OAP. The study started on June 30, 1970, and was active for 18 months. The objectives of the study were set forth by EPA in the "scope of work" and aimed toward a thorough investigation of the nature and uses of scrubbers. To achieve the specified objectives, A.P.T. conducted a literature search and surveys of scrubber users, manufacturers and researchers. What was found was then augmented with much in-house modeling and development. The products of the contract are the Scrubber Handbook, the Scrubber Bibliography and the Final Report.

Objectives

The objectives of the "Wet Scrubber System Study" were set forth by EPA (then NAPCA) as follows:

1. Evaluate current engineering technology.
2. Evaluate existing scrubber systems.
3. Investigate present usage problems.
4. Determine potential new applications.
5. Develop specific research recommendations.

Approach and Methods

The general approach to the project was to rationalize scrubber performance in terms of basic principles. This is the most powerful way to interpret experience and to extrapolate into unexplored territory. Field experience, laboratory research, and theoretical concepts were all used to relate the understanding of the fundamental mechanisms of particle separation and gas absorption to the scrubber performance. Empirical relationships were used when necessary to describe situations which have not yet been rationalized.

Whenever possible, the Scrubber Handbook presents an engineering design method based on fundamental principles, and provides original developments where no suitable methods were available in the literature.

Five surveys were carried out to get a firm grasp on the current state-of-the-art in the theory, design, and application of wet scrubbers.

(1) Literature survey - aimed at collecting all of the theoretical, experimental and practical work on wet scrubbers. Over 2,000 articles were acquired and most of them are listed in the Bibliography.

(2) Scrubber manufacturers survey - aimed at obtaining detailed information on the scrubbers currently manufactured, their performance characteristics and cost. 105 manufacturers responded with at least part of the information.

(3) Scrubber users survey - aimed at determining actual scrubber performance in various industries. Descriptions were collected of 305 scrubbers.

(4) Scrubber researchers survey - aimed at obtaining an up-to-date picture of scrubbers research and explore future research needs. 24 positive replies were received.

(5) Scrubber patent survey - aimed at collecting all scrubber patents. 250 patents were acquired.

In developing new design methods and modifying existing ones, we used what we call the unit mechanism approach. Unit mechanisms represent the essence of the phenomena on the microscopic level and permit the derivation of scrubber performance equations from basic physical principles and collector geometry. The unit mechanism equations then serve as building blocks in deriving a design equation for a specific commercial scrubber. This approach is especailly valuable for particle collection and permits the scrubber engineer to derive a theoretical design equation for his specific scrubber. Due to the hypotheses and the simplifying assumptions made in the derivations it is advisable to reinforce the theoretical equations with experimental data.

A separate chapter is devoted to scrubber design optimization. Due to the many parameters which are specific to a given industry, location or design, the method has been demonstrated for only a general case.

Existing mass transfer theories have been evaluated and assembled. Many design parameters were plotted to facilitate calculations and examples were worked out to illustrate ambiguous points. The unit mechanism path was taken to derive design equations for specific scrubber designs, especially in the more complicated case where the absorption is followed by a chemical reaction.

A research plan for filling in the identified deficiencies in the state-of-the-art and meeting the need for better scrubber performance was prepared. Priorities were assigned to research topics based on two primary criteria: (1) Pressing air pollution problems should have first priority, (2) Scrubbers should be applied in their areas of strength. The framework of time and budget for the research effort had been established in the contract scope of work. Thus the development of a research plan became a matter of fitting the most important research topics into the constraints of time and money.

Conclusions

The Wet Scrubber System Study led to the following conclusions:

1. Scrubbers are used for the removal of gases, particulates or both from a gas stream. Adequate theories, design methods and cost information are available for most of the mass transfer operations. No general approach to the design of scrubbers for particle removal was available prior to this study. The unit mechanism approach which we introduced and developed for the derivation of design methods for particle removal has proven to be powerful and generally applicable. There is still a pressing need for further development and refinement of reliable engineering design methods backed by much experimental work.

2. The scrubber designs used for mass transfer operations are those which permit long residence time and large contact area. Removal efficiency of a mass transfer scrubber depends mainly on the equilibrium relationships between the absorbed gas and the absorbing liquor. By increasing column height and by introducing a reactive substance, any desired gas removal efficiency can be achieved.

3. Particles are collected in present day scrubbers mainly by three mechanisms: inertial impaction, interception and diffusion. Inertial impaction is the collection mechanism for particles larger than ≈1 μm, diffusion for particles smaller than ≈0.1 μm and interception for particles with diameters of the same order of magnitude as the collector diameter. Fine particles in the size range of .1-1 μm are the most difficult to collect. The choice of a scrubber for particle removal depends upon economic considerations, scrubber performance, difficulty of liquor treatment, presence of other contaminants, operating conditions, materials of construction and tradition. Low velocity and low pressure drop scrubbers are adequate for relatively large particles, high velocity scrubbers are required for the removal of the 1 μm range particles.

4. Scrubbers are used to control emissions from many diversified sources and are favored over other air pollution control equipment under the following circumstances:

   a. Where the removal of gaseous, or simultaneous gaseous and particulate contaminants is required.

   b. Where the treatment or disposal of the liquid effluent is simple and not expensive.

   c. Where there is no water shortage.

   d. Where available plant space is limited.

e. Where there is an explosion hazard.

f. Where dust resistivity and/or gas temperature is high.

g. Where the dust particles are larger than ≈5 μm.

h. Where the gas is at or above the dew point.

i. Above all, where the economics is favorable.

5. Wet scrubbers account for 22% of the air pollution control market in 1971 and are projected to account for 26% of the market in 1976. Changing technology and emission regulations may lead to the future application of scrubbers to pollution control problems where scrubbers are not widely applied now. The most promising areas are the cleanup of submicron particles and inorganic gases. Scrubber application for the removal of fine particles will require the development of suitable scrubbers.

6. Scrubber research and development should be aimed at:

a. Improving scrubber performance in the fine particle range.

b. Developing a rational basis for liquid entrainment (carry-over) separation design and improving the level of performance capability.

c. Developing better and more reliable engineering design methods backed by an abundance of field data.

d. Reducing scrubber capital and operating costs and increasing scrubber dependability by decreasing scrubber size, increasing efficiency without increasing the energy required, improving water treatment methods, designing scrubbers for specific applications and developing measurement and control instruments.

Results of the Study

The results of this study are presented in two volumes:

Volume I - "Scrubber Handbook"

Volume II - "Final Report and Bibliography"

The Scrubber Handbook brings together a lot of previously scattered material and applies it in a unified way to scrubber technology. The literature bearing on particulate scrubbing was more in need of this than that on mass transfer, due to the historically greater importance of the latter. The relationship of the material ranging from basic research to field experience to scrubber technology is embodied in a general (unit mechanism) approach to scrubber analysis and design. The essence and emphasis of the unit mechanisms approach is that one should visualize and define scrubber operation in terms of the basic microphenomena which transfer the particles or the gas molecules from the gas to the liquid.

Many entirely new and many significantly improved design methods have been developed through the use of this approach and are presented in the Handbook. Thus they are useful to the engineer who needs them for design computations and to the one who can gain insight which will help him develop a new method or model.

Particle separation computations will be greatly simplified and probably made more accurate by the use of a general approach developed in this program and used in the Handbook. This approach defines the difficulty of separation as a "separation cut diameter", analogous to the number of transfer units required for mass transfer. Scrubber system optimization is discussed in general and applied to the case of cyclone type scrubbers.

Actual experience on hundreds of scrubber installations was obtained through the survey and is presented in condensed form in the Handbook. The information shown (when it was available) includes a brief description of the source process,scrubber performance data, gas and liquid stream rates and properties, costs, emission characteristics, and references. Analysis of the data to show patterns of usage, etc. are also given.

Many related topics such as auxiliaries, materials of construction, physical and chemical data, and the disposal of liquid and solid wastes are covered in thoroughly indexed chapters of the Handbook. This material will provide the reader with an overall picture of what is involved and references to additional material. Sufficient useful data are provided so that an engineer can make at least a preliminary design for a variety of systems.

The final report describes the R & D plan and the approach and methods used to achieve the objectives set forth in the scope of work. It details the organization and personnel, the various surveys, and the design method development.

The Bibliography contains about 1,700 references and is organized in a manner parallel to that used in the Handbook. Each section in the Scrubber Handbook with references has a corresponding section in the Bibliography with the same number and title.

In conclusion, we feel that the Scrubber Handbook is a turning point in wet scrubber engineering and technology, especially regarding particulates. For the first time a cohesive theory encompassing all types of scrubber design has been put forward. This theory permits every engineer, even without access to proprietary performance information, to design a scrubber with a large degree of confidence. This confidence will increase as more and more experimental information is gathered and analyzed. Attempts can now be made to extrapolate scrubber performance to areas where they have never been used before and to optimize scrubber economics and performance. It seems most likely that with this basic theory now available, with the scrubber research and development currently being carried out, and with the inherently favorable characteristics of wet scrubbers, their use will increase and they will play a growing part in air pollution control.

PROGRAM AND OBJECTIVES

INTRODUCTION

This is the final report for a Wet Scrubber System Study which was performed by A.P.T. (Ambient Purification Technology) for EPA/OAP under Contract CPA-70-95 for an 18-month period of performance beginning June 30, 1970. Companion documents which resulted from this study are a "Scrubber Handbook" and a "Selected Bibliography on Wet Scrubbers". The project director is Dr. Seymour Calvert of A.P.T. and the project officer is Mr. Dale L. Harmon of the Environmental Protection Agency.

Wet scrubbers are defined here as devices which utilize a scrubbing liquid in the separation of particulate or gaseous contaminants (or components) from a gas. They are used extensively for the control of air pollution emissions and also in chemical process systems. Since the term "scrubber" is rarely used to describe a dry system, we will generally refer to wet scrubbers as simply "scrubbers". So many different scrubber configurations have been used that there is some confusion as to whether they are all in the same category, and in some writings there is a restriction of the definition according to whether they are open or packed, etc. We intend no such limitation; any device fitting the definition of the first sentence in this paragraph is a wet scrubber.

SCOPE AND OBJECTIVES OF THE STUDY

The objectives of the Wet Scrubber System Study were set forth by EPA (then NAPCA) in the program scope of work as follows:

"(1) Evaluate Current Engineering Technology

> The selected contractor will evaluate the status of engineering technology applicable to wet scrubbers and currently available to the designers, manufacturers, and users of scrubbers... The contractor will determine the availability and adequacy of useful operational and design data, models, and equations and the applicability of these data for prediction of performance of the various types of scrubbers. Technology relating to the performance of scrubbers as both particulate collectors and mass transfer contactors should be considered... The results of this comprehensive engineering evaluation will serve as the basis for the proposed R & D program and a comprehensive authoritative handbook on scrubber technology.

(2) Evaluate Existing Scrubber Systems

The contractor will critically review and evaluate all major types of scrubbing devices currently available, assess the strengths and weaknesses of each type, and identify specific operating and maintenance problems. The contractor will identify factors that tend to limit the effectiveness of available scrubbing units for each application. Utilizing emerging technology in other fields, the contractor will identify modifications and equipment additions that could improve the performance and expand the application of wet scrubbers. The contractor will also identify specific deficiencies in existing equipment that if overcome by research and development, would improve performance and reliability and would permit expansion of the application of wet scrubbers.

(3) Investigate Present Usage Problems

The contractor will investigate current practices in the application of wet scrubbers and compile a listing of specific processes or emission problems to which scrubbers are being applied or to which application has been attempted... The contractor will investigate and identify all problems associated with present applications for each area of application and identify and quantify the major factors that affect capital and operating costs.

(4) Determine Potential New Applications

The contractor will investigate and identify major air pollution sources that are amenable to control by the use of wet scrubbers, including sources that are normally controlled by other types of devices... The contractor will estimate the magnitude of each collection problem and identify factors currently limiting the application of scrubbers in these areas.

(5) Develop Specific Research Recommendations

Two 5-year research and development programs, Plan A and Plan B, are to be developed as a product of this study... Each plan will recommend specific research and development required to provide technology where deficiencies exist and generate needed data to improve process performance and economics to permit expansion of wet scrubber application to the control of additional air pollution sources."

The major products of the study are the handbook, research plan, bibliography and final report. The objectives for each of these may be briefly stated as follows:

Scrubber Handbook - The handbook is to be an authoritative and comprehensive source on wet scrubber technology. It includes in-depth engineering analyses and is intended for use in design, research, and instruction.

Research Plan - The research plan is aimed at overcoming the identified deficiencies in the state-of-the-art. The research plan reflects the need for better separation of present scrubbers, improved capabilities of future scrubbers, lower costs, and optimum application to specific processes. It provides guidelines to both the sponsors and the performers of research.

Bibliography - The bibliography is to serve as a guide to the most useful items of published literature and government reports which relate to wet scrubbing.

Final Report - The final report is to document the method, results, and conclusions of the scrubber study. The research plan is presented in the final report.

APPROACH AND METHODS

GENERAL APPROACH

The general approach to the project was to rationalize scrubber performance in terms of basic principles. Field experience, laboratory research, and theoretical concepts were all to be used in relating a quantitative understanding of the fundamental situations, in which both particles and gases are transferred from the gas phase to the liquid, to the performance of the scrubber.

Given sufficient understanding, one can develop an engineering design method which enables the predication of performance with reasonable confidence. Wherever possible we would present such a method based on fundamental principles, and would provide original developments where there were not suitable methods available in the literature. Empirical relationships are used when necessary to describe a situation which has not yet been rationalized.

As the first step in this approach, one needs an overall concept of scrubber systems and the basic phenomena involved. Then he can describe the overall problem in terms of a number of related components. Having defined the problem, one next needs to establish priorities for work on the various components.

Since there is always a limit on what can be accomplished, it was intended that this approach would ensure that the most important things would be covered. Figure 1 is a schematic diagram of a scrubber system which has nearly everything imaginable and reasonable. It serves as a pictorial check list of what ought to be considered. Along the same vein, a detailed outline of all conceivable methods of gas purification by scrubbing was prepared and used as a guide for the study. This outline is well represented by the Tables of Contents for Chapters 4 and 5.

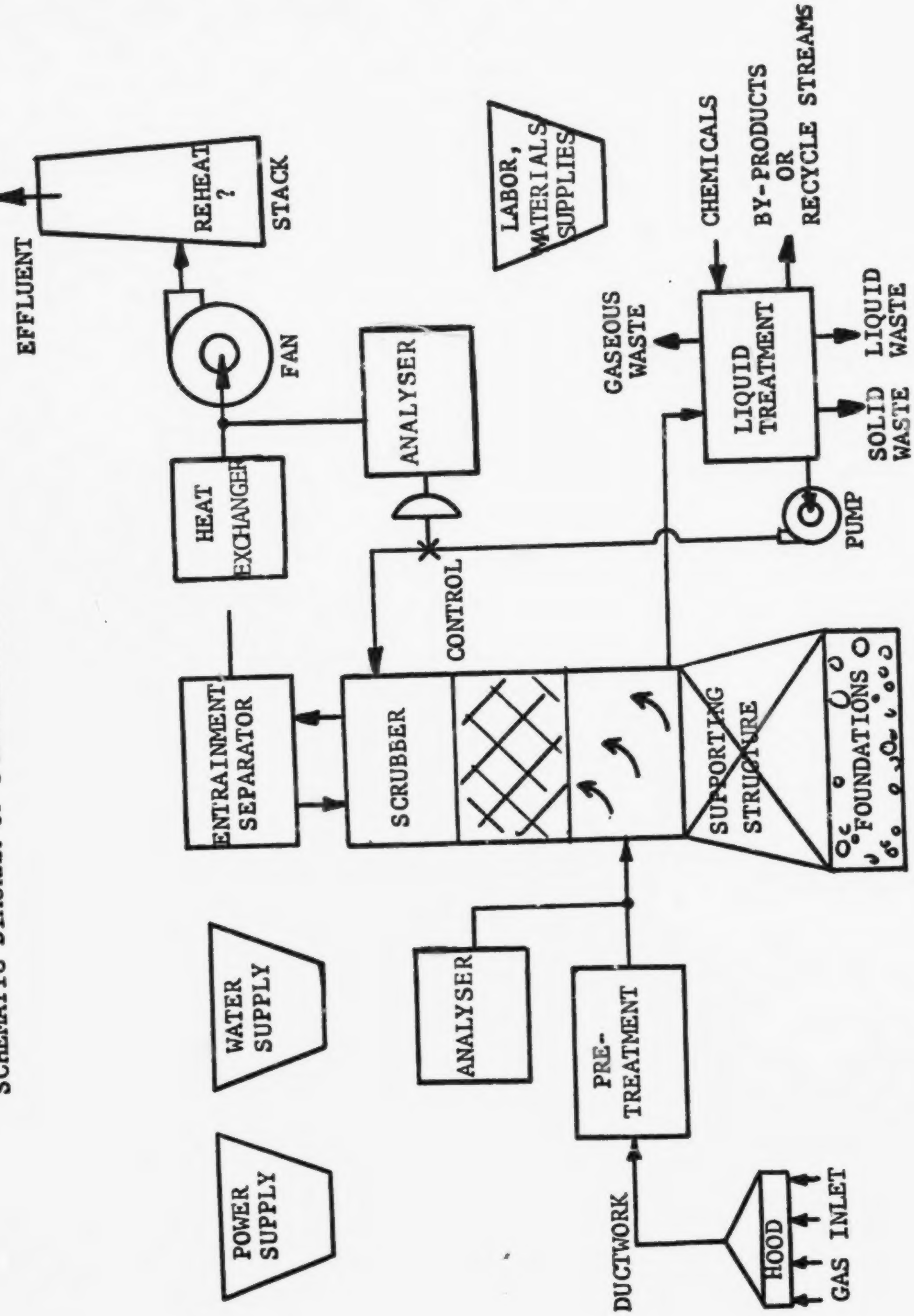
The Handbook is composed of material which is the result of activity in three main areas.

1. Review and development of engineering design methods related to scrubber performance.
2. Review and development of engineering information on system elements other than the scrubber itself.
3. Aquisition and analysis of actual experience data (surveys).

In the development of design methods the general approach, and an ideal not completely realized in all cases, was to:

Figure 1

SCHEMATIC DIAGRAM OF SCRUBBER SYSTEM


EFFLUENT
REHEAT ?
STACK
FAN
LABOR, MATERIALS SUPPLIES
CHEMICALS
BY-PRODUCTS OR RECYCLE STREAMS
GASEOUS WASTE
LIQUID TREATMENT
LIQUID WASTE
SOLID WASTE
PUMP
ANALYSER
HEAT EXCHANGER
CONTROL
ENTRAINMENT SEPARATOR
SCRUBBER
SUPPORTING STRUCTURE
FOUNDATIONS
WATER SUPPLY
POWER SUPPLY
ANALYSER
PRE-TREATMENT
DUCTWORK
HOOD
GAS INLET

1. Analyze all currently known wet scrubbers of significance and define them in terms of the elemental physical and chemical mechanisms (unit mechanisms) which are the components which can be assembled to describe any kind of scrubber.
2. Develop a set of the best available design methods (i.e., mathematical models relating design variables to performance) for each of the unit mechanisms. Utilize the best available design information but do not be limited by it. Where gaps or weak points exist, develop new or improved methods.
3. Synthesize the appropriate total design equations from the unit mechanisms equations and use them to predict performance of known types of scrubbers.
4. Utilize available published and unpublished design methods, performance data, manufacturers' literature, etc. to predict performance of the systems covered in point 3, above.
5. Compare the predictions of the available methods (point 3) and the available information (point 4). Reconcile differences to firm-up the final models and to elucidate areas for further research. Where performance data are limited, indicate the range of possible error associated with the recommended method. Indicate any limitations on scale-up capability.
6. Develop charts and tables for the reader's convenience in making design computations.
7. Present example calculations to illustrate the use of design methods.

As Figure 1 indicates, there are a number of elements other than the scrubber which make up the total system. Frequently the technology or cost of one of these is more significant than that of the scrubber itself. There are other considerations which may limit performance or feasibility. The kind of factors studied are as follows:

1. Equilibrium considerations and related problems such as physical solubility, chemical reaction equilibrium, rate of chemical use, solvent losses, and solvent selectivity.
2. Operating characteristics such as stability, reliability, flexibility, and controllability.

3. Auxiliaries such as blowers, pumps, heat exchangers, lines, spray nozzles, controls, hooding, venting, liquid clarification for recycle, liquid chemical treatment, crystallizers, solvent stripper, extractors, and liquid or solid waste disposal.
4. Measurement of system performance by means of manual or machine sampling and analysis of gas and liquid streams.
5. Operating and maintenance labor, materials, and other costs.
6. Health and safety considerations such as toxic gases or liquids, explosive materials, hot surfaces, and corrosive or irritant materials.
7. Materials of construction problems such as corrosion, erosion, strength, weight, ease of repair, susceptibility to stress and fatigue, and cost.
8. Economic factors and their analysis such as determining costs for investment, power, chemicals, operating labor, maintenance, and depreciation.

ORGANIZATION OF PROGRAM

Implementation of the general approach described above required that the program activities be organized into functional **subdivisions** which could be treated as individual work assignments and responsibilities. It was decided that the most efficient way to proceed would be to set up a tentative outline of the final report-handbook combination and to assign responsibilities and deadlines for various sections of the outline.

By proceeding in this way the results would be written up in final format as soon as possible. This would provide the maximum time for review, rewriting, and reorganization. It will be recognized that the interdependencies of one task on the result of another, and the unexpected turns of events gives rise to an incessant reordering of efforts as new needs become apparent.

PERSONNEL AND SUBCONTRACT

The program technical personnel involved the staffs of APT, a sub-contractor, Garrett Research and Development (GRD), and consultants. The individuals involved were as follows:

APT

Seymour Calvert, Ph.D., Project Director
Jhuda Goldshmid, Ph.D.
David Leith, M.S.
Dilip S. Mehta, Ph.D.
Amancio Sycip, M.S.

GRD

John Ellis, B.S.
George Preston, Ph.D.
Edgar Manker, Ph.D.
Jerome Wilkenfeld, M.S. (Hooker Chemical)

Consultants on Optimization

Lucien Schmidt, M.S.
Jack Alkalay, Ph.D.

The subcontract with GRD, a subsidiary of Occidental Petroleum, was for the period of 11 months and was mainly intended to provide access to the various components of Occidental for data on their scrubber experience. These included Hooker Chemical, Occidental Chemical, Island Creek Coal, and others. Some of the GRD personnel contributed to the preparation of technical material for the handbook. Dr. Preston was largely responsible for Chapter 10 and several sections of Chapters 4 and 5. Mr. Ellis was largely responsible for Chapters 6 and 11, several sections of Chapter 9, and the compilation of a considerable amount of survey data for Chapter 7.

Many people and organizations contributed generously to the scrubber system study, and their part in the preparation of this book is gratefully acknowledged. We wish especially to point out the important parts played by Mr. Dale L. Harmon, project officer for the study, and Messrs Robert Lorentz and Richard Harrington of the Environmental Protection Agency. Dr. Leslie Sparks, project officer during the final period of the study, contributed notably to editing the Handbook and this Report.

Some of those whose contributions were most noteworthy are the following:

Allegheney County Health Department, Bureau of Air Pollution Control, for providing information on the performance of scrubbing systems.

Professor P. H. Calderbank, papers on bubble dynamics.

County of San Bernardino Air Pollution Control District, for providing information on the performance of scrubbing systems.

Bureau of Air Quality and Noise Control, Department of Environmental Resources, Commonwealth of Pennsylvania.

Department of Environmental Control, City of Chicago, for providing information on the performance of scrubbing systems.

Department of Public Health and Welfare, Division of Air Pollution Control, City of Cleveland, for providing information on the performance of scrubbing systems.

Department of Water and Power, City of Los Angeles, for providing information on the performance of scrubbing systems.

Environmental Protection Agency, Office of Solid Waste Management Program, incineration.

Harvard School of Public Health, for providing information on the performance of scrubbing systems.

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New Jersey State Department of Environmental Protection, for providing information on the performance of scrubbing systems.

Oak Ridge National Laboratory, for description of scrubbers used in their installation, and description of their work on scrubbing of materials released due to an accident.

Tennessee Valley Authority, Division of Chemical Development.

For her tireless and careful work in the typing and reproduction of this report, we express our appreciation to Mrs. Glenna Paschal.

SURVEYS

Five surveys were carried out to get a firm grasp on the current state-of-the-art in the theory, design, and application of wet scrubbers. The purpose of the surveys was to broaden the base of the scrubber study by studying the first hand knowledge and experience of as many people as possible who work with scrubbers.

Each survey was aimed at a specific goal. Results of the surveys were used wherever possible in the writing of the Wet Scrubber Handbook. The persons or material surveyed, and the main use of the results obtained is given below:

2.4.1	Literature	Chapters 4, 5, 6, 7, 8, 10, 11, 12
2.4.2	Scrubber Manufacturers	Chapters 3, 5
2.4.3	Scrubber Users	Chapters 7, 8
2.4.4	Researchers	Chapters 4, 5, and final report
2.4.5	Patents	Chapter 3

Documentation on the method of approach and analysis of data obtained in these surveys will be given for each survey.

Literature Survey

An extensive and in-depth survey of the literature was performed in order to find all theoretical, experimental, and practical work on wet scrubbers which has been reported.

Abstracting services were utilized. Computer printouts of relevant literature references were received from APTIC, NTIS, AEC, NASA and Midwest Research Institute. Chemical Abstracts and British Chemical Engineering Abstracts were consulted.

A direct manual search of forty-eight technical journals carrying articles pertinent to scrubber systems was carried out. Twenty-five journals were searched from 1950 to present; the balance from 1960 to present. Facilities of UCLA, California Institute of Technology and the University of California at Riverside were used.

Of the thousands of literature articles reviewed, about 2,000 were judged directly pertinent to the Wet Scrubber Study, and were acquired, classified, and filed in the APT library. These were used throughout the writing of the handbook and are listed in the Bibliography.

Most of the evaluation of literature came at the time that the literature was being screened for articles relevant to the scrubber study. If an article was judged as contributing to the knowledge of scrubbers, it was noted and acquired. If there was doubt as to the contribution of an article to scrubber understanding, it was also noted and acquired. It was deemed prudent to select all articles which might be of use in the scrubber study, rather than be overly selective at the outset, and reject these articles.

Throughout the course of the work on the Wet Scrubber System Study, articles extracted from the literature were consulted. Evaluation of these articles continued throughout the work, and comments on them are at appropriate places in the Wet Scrubber Handbook.

Scrubber Manufacturers

To obtain detailed and up-to-date information on the scrubbers currently manufactured, their performance characteristics, costs, and makers, a survey of scrubber manufacturers was made. Similar surveys were made of manufacturers of mist elminators, gas absorption equipment, and fan manufacturers.

The names and addresses of manufacturers were taken from three sources: Chemical Engineering Magazine - "Environmental Engineering Deskbook Issue", 77, 9, (April 27, 1969); Environmental Science and Technology's "1969-1970 Pollution Control Directory", 3, 10 (Oct. 1969); and the "1970-71 APCA Directory", published by the Air Pollution Control Association.

A letter requesting information describing the scrubbing equipment made, cost data, and case studies was sent to 250 manufacturers. A copy of the letter sent to scrubber manufacturers and the enclosed sheet describing the scrubber study are given in Appendices A and B. Similar letters were sent to manufacturers of mist eliminators and gas absorption equipment. A letter and data sheet for return to APT was sent to an additional ninety-six fabricators of scrubbers, to get information on the availability and price of the scrubbers and auxiliaries they make. More detailed information was requested from nine of the largest manufacturers.

Of the 250 letters to manufacturers sent out requesting information, 105 manufacturers responded with at least some of the information requested. A total of 26 declined to send information, most because they were no longer in the scrubber business.

Several large companies, members of the Industrial Gas Cleaning Institute, (IGCI), referred us to the IGCI for information on their scrubbers. Most IGCI members responded directly to our requests without referral to the IGCI. The IGCI was contacted by letter and telephone, but did not supply information on the scrubbers of its member companies. The balance of the companies contacted were either duplicates, or else chose not to respond to our requests.

Most scrubber manufacturers either did not have, or else did not wish to disclose detailed information on the performance of their products. It was decided that the fairest way to describe all manufacturers' products would be to classify them according to the types of scrubbers supplied, and then list the names of the manufacturers of each type of scrubber alphabetically. This is done in Chapter Three of the Handbook. Additional information on the performance of certain manufacturers' products was used in writing Chapter Five, "Design Methods".

Surveying a group of manufacturers is treacherous on two accounts: (1) Some manufacturers may be listed who do not or no longer manufacture the products they are listed for, and (2) manufacturers who do manufacture applicable equipment may not be included. With regard to the first point, all the manufacturers listed in Chapter Three of the Handbook informed APT that they were currently selling the equipment listed as of the time of writing Chapter 3, Spring 1971. A sincere effort was made to contact all scrubber manufacturers. Still, some manufacturers are undoubtably not listed in Chapter Three. This may be because they were not listed in our manufacturers sources, or because they did not respond to our inquiries.

Scrubber Users

To find out how well scrubbers perform in controlling the emissions from industrial processes, a survey of industrial scrubber users was carried out. The objective was to determine liquid rate, gas temperature, pressure drop, collection efficiency, capital and operating costs, maintenance problems, characteristics of gas and scrubbing liquid, size distribution of dust, power consumption, and characteristics of product collection for specific processes to which scrubbers are applied. To develop this information, three methods of approach were used: direct solicitation of data through firms managed by the sub-contractor, Occidental Petroleum Corporation; inspection of appropriate files of cooperative air pollution control agencies; and a mail survey of scrubber users. Each of these methods of approach will be briefly described.

Occidental Petroleum has a number of subsidiaries operating in fields where scrubbers are frequently used for the control of air pollution. The appropriate facilities were identified and contacted by the subcontractor. Data were obtained on a four-page questionnaire, specifically designed to extract all pertinent information while retaining sufficient generality to apply to any conceivable scrubber. The form used is given here as Appendix D. In all, data on sixty scrubber systems were obtained by the subcontractor.

In conjunction with the mail survey (to be described later) seventy-five municipal and state air pollution control agencies were contacted. A number of the agencies were willing to provide performance data on scrubbing systems operating in their areas of jurisdiction. All together, fairly extensive performance data on one hundred thirty-one scrubbing systems were obtained from control agencies. In all cases it was necessary to visit the agency and spend several days there, to obtain information of sufficient detail to be useful.

A survey by mail was conducted to develop performance data for additional scrubbers. The main tasks in the mail survey were to: (1) identify by name and address known and potential scrubber users, (2) find out if these users had information on the performance of their scrubbers which might be used, (3) if so, obtain this information.

Names and addresses of scrubber users were requested in seventy-five letters to state and local air pollution control officials listed in "1970-71 Directory, Governmental Air Pollution Agencies", published by the Air Pollution Control Association. Of the seventy-five contacted, twenty-four provided lists of scrubber users, seventeen either declined or were unable to provide lists, and thirty-four made no reply.

American Industrial Hygiene Association (AIHA) local chapter presidents were contacted. Of the thirty approached, two gave lists of users, seven chose not to provide lists, and twenty-one made no reply.

Fifteen likely trade organizations were asked to provide lists of their members using scrubbers. Three did so, five did not, and seven did not reply.

In addition, likely scrubber users were identified in the "California Manufacturers Index, 1970-71".

In all, 1,518 names and addresses of companies using scrubbers throughout the United States on a wide variety of industrial processes were identified. Each of these was sent a letter explaining the objectives of the scrubber study, and requesting their participation in the task of gathering performance data by filing in and returning an enclosed post card. This letter is given in Appendix C. Two hundred sixteen replies were received; one hundred thirty-two said they chose not to participate in the survey, while eighty-four said they would.

The eighty-four users willing to participate in the survey were next sent as many copies of the complete, four-page questionnaire in Appendix D as they had scrubbers. A covering letter was enclosed. Meanwhile, the Federal Facilities Branch of EPA had identified seventy-five government scrubber installations. Scrubber manufacturers also provided names and addresses of scrubber users. Because many of the users had more than one scrubber, about five hundred of the four-page questionnaires were sent out.

If after about two months no reply to the questionnaire had been received, a reminder was sent. Enclosed was a condensed version of the four-page questionnaire, the thought being that lack of response might be due to the detail in the four-page version. See condensed questionnaire, Appendix E. About this time, the subcontractor provided the names and addresses of twenty-six large companies who were thought to be using scrubbers. Most had already been contacted, but had not responded. They were sent another letter, with copies of the condensed questionnaire enclosed. One hundred fourteen completed questionnaires were received as the result of the mail survey.

The total response to the scrubber users survey was, then: sixty from the subcontractor, one hundred thirty-one from visits to cooperative control agencies, and one hundred fourteen from the mail survey for a grand total of three hundred five scrubber systems described. This material was used to write Chapter Seven, "Scrubber Performance on Industrial Emissions"and part of Section 8.4.

The information obtained in the scrubber users survey was almost always fragmented, and was reported in any one of a number of systems of units. To make the results useful, it was necessary to convert the data reported into a consistent system of units, and then condense the data into a useful, working format. To remain consistent with the Handbook, cgs units were used in reporting the data obtained. Chapter 7, where the user's data is presented, also has a brief table of conversion factors, to enable conversion from cgs to engineering units and vice versa.

Only in a few cases was there information reported on the properties of the gas and/or particles going into the scrubbing system. This is because most scrubber performance tests from which the users' data came had been performed on the scrubber's outlet side only, to see if the scrubber passed an emission code. As inlet gas and particle properties are important, typical inlet characteristics for each process discussed in Chapter seven were found in the literature and reported.

Some of the survey results were so sketchy as to be of questionable worth. These results were discarded, and are not reported. On the other hand, some worthwhile scrubber performance data were found in the literature. These data were included in the data analysis given in Chapter Seven.

Scrubber Researchers

Our literature survey accounted for past work and accomplishments in the field of wet scrubbers. To get the present day picture we conducted a scrubber researchers survey. The purpose of this survey was threefold: (1) Obtain an up-to-date picture of wet scrubber research, so that present day work would not be duplicated in our proposed research plan. (2) Explore future research needs by asking the various investigators in the field. (3) Complete the wet scrubber bibliography study by requesting copies of pertinent articles.

We requested the information through a letter mailed to the various investigators involved in the study of wet scrubber systems and/or technology, together with researchers found to be studying the topic. A list of addressees was obtained from the following sources: (1) Chemical Engineering Department heads in most of the U.S. Universities and many in Western Europe. (2) Researchers listed in the APCA directory. (3) Participants in APCA, A.I.H.A., A.I.Ch.E. and other scientific meetings held during 1970-71 where topics related to wet scrubbers was discussed. (4) "Air Pollution Titles", published annually by the "Center for Air Environment Studies", Pennsylvania State University. (5) Authors of pertinent literature articles. (6) Consulting engineering firms active in the field of wet scrubbers.

All together 194 letters were sent. We got back 44 replies out of which 24 were positive, discussing present and past research in fields related to wet scrubbers. Twenty replies were negative and provided no information. Most of the suggestions for future work were found important and are included in the five-year research plan presented later in this report.

We did not request and did not get information on present research and development work carried out by the various wet scrubber manufacturers. We met with several of the larger manufacturer's engineers and always found that this kind of information was classified.

To summarize, we think that between the literature study and the researchers survey, despite the low response, we got a good picture of present day knowledge and future research requirements.

Patents

A survey of patents related to scrubbers as listed in the U.S. Patent Office was carried out, mainly in the Patent Office Search Room in Washington, D.C. About two hundred fifty patents on scrubbers were identified, noted, and acquired. The patents were classified according to the type of device patented, and used in the preparation of the "Scrubber Patents" section of Chapter Three.

DESIGN METHOD DEVELOPMENT

In developing new design methods and modifying existing ones, we used the unit mechanisms approach. Unit mechanisms are defined in Chapter Four of the Handbook as follows: "Unit mechanisms for mass transfer and particle collection are the basic physical and chemical situations in which contaminants are taken out of the gas." Each unit mechanism describes an interaction between a force or a gradient, a physical configuration of the collector and a gaseous or particulate contaminant. Once unit mechanisms for various couples - of force and collector configuration - have been quantitatively described, and their arrangement in the collecting equipment defined, an equation predicting the collection efficiency of this particular equipment can be derived. Furthermore, after an equation describing the behavior of a control device is available, the effect of the change in various parameters on it's performance can be analyzed. This approach yielded many of the design equations given in the Handbook and with further development and refinement promises even better results. In the following pages the methods of how this approach was utilized will be described in some detail.

Basic Concepts

As defined above, a unit mechanism is a function of the force acting on the particles, or the gradient in the case of mass transfer, and the collector geometry only. It is assumed that variation in the properties of the gaseous contaminant, particulates and scrubbing liquid can be neglected. Table 1 shows all the important combinations of force and geometry. Not all of the important combinations are significant; for example, gravitation is expected to be insignificant in liquid and gas jets due to the very high inertial effects.

TABLE 1

UNIT MECHANISMS FOR PARTICLE SEPARATION

	Grav.	Inertia	Brownian Diffusion	Electrostatic	Flux Forces
1. Drops	S	S	S	S	S
2. Cylinders	N.S.	S	S	S	S
3. Bubbles	N.S.	S	S	S	S
4. Sheets	S	S	S	S	S
5. Liquid Jets	N.S.	S	S	S	S
6. Impacting Gas Jets	N.S.	S	S	S	S

Note: N.S. indicates that this unit mechanism is not significant.

To derive quantitative expressions for the various unit mechanisms, equations describing the different forces are required. These were reviewed and discussed in the "Basic Concepts" Section. This section of the Handbook is an extensive literature review of the various aspects of mass transfer and the different forces affecting particle motion. It reviews the different mass transfer theories, mass transfer with and without chemical reaction, and mass transfer to slurries. Gravitational, inertial, electrostatic, diffusiophoretic, and other forces which act on particles are discussed. Mechanisms leading to particle growth are also discussed since the particle diameter, or aerodynamic diameter enters many of the unit mechanism equations.

Attention was then shifted to drops and bubbles, which are the collection bodies most frequently encountered in wet scrubbers. The literature was reviewed for equations and experimental description of their shape, size and hydrodynamic behavior under a multitude of operating conditions.

With this information on hand, equations describing various unit mechanisms could now be derived. Several equations, such as collection of particles by spheres, or impaction from various shape jets, were already available in the literature. Others were derived by considering the known force acting on the particles in the neighborhood of the collector.

Sometimes several forces act simultaneously on the particles. They either act all in one direction, or oppose each other. In these cases the combined effect was obtained by summing the individual fluxes, which is the same as summing the individual forces.

Unit mechanisms are affected by changes in the operating conditions of the scrubber. Variation in gas flow rate are accounted for in the unit mechanism equations. Changes in liquid flow rate usually affect the concentration of available collecting bodies or the aerosol residence time and are accounted for in the integrated design equations. Changes in particle and liquid properties, except for particle diameter and density, were not considered in deriving the design equations, though they should be, due to lack of adequate theories and experimental data. However, their importance was always emphasized.

Effects of changes in operating pressure and temperature on the different unit mechanism were analyzed and discussed in Chapter 4. Opposing views found in the literature regarding the effect of particle concentration on collection efficiency and on the unit mechanism equations were quoted. However, it is our opinion that so long as particle concentration is below the level where particles hinder the movement of one another, their concentration does not effect collection efficiency.

Design Methods for Various Scrubber Groups

The unit mechanisms equations can be used as building blocks to obtain design equations for various scrubber designs. The first step is to analyze the scrubber in question; find out how the gas flows, what serves as particle or gas collector, and what shape the collector takes. Are there several different collection stages and are they arranged in series or parallel to one another? What is the total collecting surface area, what percentage of the theoretically available collecting area is actually used, and what percentage is wasted? Is there an appreciable change in particle properties when passing through the collector, what forces are responsible for collection, and what is their magnitude? In most cases the force magnitude is a direct function of another quantity, such as relative velocity between particle and collector, temperature gradient, humidity, etc.

When analyzing the various collecting devices available in the market, we found out that they can all be grouped in ten basic groups. The same unit mechanisms, namely the same force and collector geometry, is responsible for all, or the major part of the collection in all the devices which belong to one group. The various devices within one group usually differ in flow rates, percentage active collecting surface area, and the changes in particle and liquid properties which take place within the device. A commercial scrubber may include more than one collection device in one unit. For example, in the "mobile bed" scrubber the gas passes first through a liquid spray, then through a sieve plate, a packed bed, a foam region, and finally exits through a baffled entrainment separator.

When only one unit mechanism applies, or when one mechanism is responsible for most of the collection, integration over all the collecting bodies yields the collection efficiency equation for the device. Collection equations so derived were then tested against experimental results. In some cases the agreement with theory was good, in others, curve fitting yielded the experimental coefficients required for closer description and prediction of the efficiency. In the "mobile bed" example given earlier, it was felt that the packed bed section contributes the major part of the collection. Thus the packed bed unit mechanism equation was compared with experimental results for mobile beds and the experimental coefficients determined.

The major difficulty encountered when using this procedure for deriving the design equations in the Handbook, was the lack of good and reliable collection efficiency data.

Evaluation of Available Methods

When conducting the literature survey various design methods for different scrubbers were found. Several of these methods are empirical while others are based on a theoretical approach. However, we did not find any attempt to unify the field of particle collection through one approach as we did through the unit mechanism. No existing design method claimed to be an overall wet scrubber theory for particle collection. The literature on mass transfer in more extensive and several theories which cover the field from different angles are available.

A few of the particle collection equations found in the literature were adequate for our unit mechanism approach and were included in the Handbook. These included: Langmuir and Blodget approach and solution to the collection by spheres and cylinders, Davies equations for impacting jets and deposition on ducts and pipes, Calvert's equations for Venturi and packed column, and several others.

In other design methods found in the literature, an empirical approach was taken and empirical equations or rules resulted.

The major disadvantage of these empirical methods is that they could not be applied outside the domain that they describe and they can not make predictions. An example is the power law, which is a good rule of thumb if applied within its range of application. However, as shown in the Handbook through the venturi equations, this rule gives only a partial picture and can only correlate data already at hand.

Whenever existing equations, that were not derived through the unit mechanism approach, were available, these equations were compared together with our derived equations to available experimental results. All the design methods are usually listed in the Handbook and the one that agreed best with experimental results is recommended.

Augmentation of Methods

The major obejctive of the "Basic Concepts" and "Design Methods" chapters in the Handbook is to present a unified approach to the field of particulate scrubbing. Wherever design methods are not available for existing devices, or when a designer has a new wet scrubber in mind, the equations or the approach presented in the Handbook should be used to obtain a suitable design method.

Many of the design equations are plotted in the Handbook to help the design engineer see the trend resulting from changes in the equipment geometry or the operating variables. These plots also reduce the calculation time required for the prediction of equipment performance. Design examples are presented in Chapter 9 to clarify the calculation methods when employing these charts.

Simple approximate estimation methods based mainly on the particle aerodynamic diameter as a measure of the difficulty of separation are also presented. With the help of this estimation method one can obtain a fast approximation of the type and size of equipment that will give the desired collection efficiency.

Example Problems

Example problems are used where necessary in the book to illustrate a concept or an approach to solving a problem. In those sections dealing with the theory of scrubber design and performance, primarily Chapters 4 and 5, example problems are intertwined with the text, and serve to point out how a particular point or equation discussed can be used. Chapter 9 is entirely devoted to example problems and shows how the design methods discussed earlier in the Handbook for calculating the design of various components of a scrubber design can be used to engineer a complete scrubbing system.

The example problems, or design examples, illustrating a particular point are as follows:

4.2.6.4	Instantaneous Reaction Criteria
4.2.7.5	Reactive Solids Slurry
4.5.1	Unit Mechanisms for Mass Transfer: Drops (2 Examples)
4.5.2	Unit Mechanisms for Mass Transfer: Bubbles (2 Examples)
4.7	Effect of Pressure & Temperature on Collection of Particles in Wet Scrubbers
5.2.2.2	Column Diameter (Plate Columns)
5.2.2.3	Pressure Drop (Plate Columns) (2 Examples)
5.2.2.4	Column Height (Plate Columns)
5.2.3.2	Column Diameter (Packed Column)
5.3.3.2	Particle Collection Efficiency (Packed Column)
5.3.4.7	Fiber Packing: Particle Collection Efficiency
5.3.10	Mechanically Aided Scrubber: Particle Collection (2 Examples)

The example problems listed in Chapter 9 are more extensive and serve to bring together the approaches to designing a scrubber system and its components described in earlier chapters of the Handbook. Chapter 9 is for the purpose of clarifying the design methods, enabling the reader to check his calculation method for computational errors, and for tying a few loose ends. Most of the examples center on the scrubber performance itself and a few are fairly extensive. Mass transfer examples are presented in Chapter 5 in many instances, for more effective relationship to the text, but they are listed under 9.3.2 to ensure that the reader can find them.

Some discussion of "trouble shooting" (i.e. the solution of operating problems) is given in Section 9.4. Recognition of the sorts of possible difficulties one may encounter has an obvious beneficial effect on the design of scrubbers. Thus the last part of this chapter serves as a reminder of the many factors besides scrubber efficiency to consider in system design, selection, operation, and maintenance.

The example calculations presented in Chapter 9 are listed below:

- 9.3.1 Particle Separation Calculations
    - 9.3.1.1 Plates
    - 9.3.1.2 Packed Beds
    - 9.3.1.3 Fiber Bed
    - 9.3.1.4 Preformed Sprays
    - 9.3.1.5 Gas Atomized Spray
    - 9.3.1.6 Centrifugal
    - 9.3.1.7 Secondary Flow
    - 9.3.1.8 Impingement and Entrainment
- 9.3.2 Mass Transfer Calculations
- 9.3.3 Mass Transfer with Chemical Reaction Calculations
- 9.3.4 Example Problem: Coal Dryer Exhaust
- 9.3.5 Example Problem: Application of Diffusiophoresis and Particle Growth to a Rock Wool Cupola
- 9.3.6 Example Problem: Phosphoric Acid Plant Fluoride Scrubbing

9.4 Trouble Shooting

OPTIMIZATION

Optimization is a procedure used in the design of a process, such as a scrubbing system, which helps make the process design "best" in some regard. Two criteria frequently encountered in the design of scrubbers are cost of the scrubber system (to be minimized), and performance or efficiency of the system(to be maximized). Other measures might be ease of maintenance, low space requirement, reliability, or any other factor which contributes to the scrubbing systems relationship with the job it has to do.

Frequently, optimizations from more than one standpoint are carried out simultaneously. For example, it might be desired to design a scrubber to achieve maximum efficiency at minimum annualized cost. The data inputs with which optimization is carried out will vary depending upon the situation of the designer. For example, water and power costs can vary widely according to local rates, and the quantity the user consumes. An economic optimization based upon one set of economic data would show different results from a similar optimization based upon different economic inputs. It is difficult if not impossible to give meaningful results from an optimization procedure for the design of wet scrubber system from any standpoint, without making a number of crucial assumptions which may or may not reflect the situation a practical designer faces. Optimization results based on incorrect assumptions can be highly misleading.

The methods and techniques used in an optimization procedure and examples of how these techniques might be used in a realistic optimization problem are presented in Section 8.5 of the Handbook.

In Section 8.5, first the general approach to optimization is discussed. The application of these principles to scrubber design is illustrated by the optimization of a venturi scrubber for maximum efficiency at a fixed pressure drop. A more complex optimization procedure is illustrated for the performance of a cyclone collector.

Another possibility for optimization may lie in using several collectors in series or in parallel. An example of devices in series might be a cyclone precleaner before a venturi or centrifugal scrubber controlling the emissions from an asphalt plant drier, or several impingement plates in series in a single impingement plate scrubber. Section 8.5 discusses the manner in which the efficiency of collectors in series or in parallel can be calculated, and the subsequent pressure drop.

OTHER AREAS FOR APPLICATION

The search for potential new applications for scrubbers is essentially a matter of reviewing the control technology for specific air pollution sources and identifying those areas which report no use or limited use of scrubbers. There are usually some reasons given for not using scrubbers and one must examine them and then speculate first as to whether they are valid. In some cases, for instance, it is stated that scrubbers are not used because they are incapable of providing high enough collection efficiency, while in reality this judgment is based on outdated or incorrect information. We can readily determine or predict whether a desired level of performance is attainable.

In other cases the reason that scrubbers are not used is that they are too expensive. Dealing with this question is more difficult than predicting performance. So many factors enter into the economics of a process that they must be dealt with pretty much on an individual case basis. Thus, we can generalize that scrubbing would be worthy of consideration for a certain type of application, but one would have to check it out in detail to get realistic costs.

Some applications would be rather far-fetched, although we would hesitate to say impossible. Space limitations, the undesirability of a system which requires any attention, corrosion problems, liquid supply or disposal limitations, and other constraints may rule out scrubbers; at least as now available.

The "check lists" of potential applications were obtained from various publications and reports dealing with either source control or device applications, from our survey of users and manufacturers, and from speculation and analysis by staff members. Judgments of potentiality were made in the light of the scrubber system study.

RESEARCH NEEDS AND PLAN

Paragraph (5) in the "Scope of Work" described the objectives and scope of the research plan as follows:

"(5) Develop Specific Research Recommendations

Two 5-year research and development programs, Plan A and Plan B, are to be developed as a product of this study. Plan A should be based on an assumed total expenditure of two million dollars. Plan B should be based on an assumed total expenditure of seven million dollars. In each plan, priorities should be assigned to the various component projects to allow for program flexibility."

"Each plan will recommend specific research and development required to provide technology where deficiencies exist and generate needed data to improve process performance and economics to permit expansion of wet scrubber application to the control of additional air pollution sources. Each recommendation for research should include an indication of priority and a detailed description of the research proposed, including the purpose, goals, proposed work statements, recommended approach, and estimated time and cost schedules."

The approach taken was to analyze and review each research subject, determine if it provides technology where deficiency exists and if it improves process performance and economics of wet scrubber application - in line with the requirements set forward in the "Scope of Work". Priorities were determined by evaluation of pressing industry needs in relation to wet scrubber areas of strength (a more detailed discussion is given in the "Research Plan" Chapter).

To prepare the two research plans called for in the "Scope of Work" we followed this 7 point procedure:

1. All the members of the Wet Scrubber Project staff were requested to write down the research needs and ideas which occurred to them during the work.

2. Research needs were also obtained through the researchers survey.

3. The research ideas were collected once a month and circulated to the project staff.

4. The ideas were reviewed and analyzed periodically to determine their relevance, need and priority.

5. When preparing the final report all the ideas were again screened and had their final priority rating determined.

6. The cost, time and manpower required to achieve the established goals of the various ideas were estimated.

7. Two final research plans were determined. The various projects were arranged according to their priority, logical time order and reduced load in the first and last years to allow phasing in and out.

The two research plans are submitted in the chapter on the "Research Plan". The research subjects were chosen and written in accordance with the guide lines established in the "Scope of Work." Priorities were assigned following the reasoning established in the "Research Plan" Chapter.

RESULTS

SCRUBBERS AVAILABLE

Many different scrubbers are offered for sale by many companies. Still more scrubbers have been patented, but are not currently being manufactured. Due to the diversity in scrubber design, performance, and cost, statements broad enough to apply to all scrubbers are so general that they are seldom useful. However, it is possible to divide the various types of scrubbers into ten groups based largely on their operating principles. The characteristics of each group can then be discussed in more specific terms than would otherwise be the case.

These groups provide the framework for discussing scrubber design (Chapter 5) and experience (Chapter 7) in the Handbook. The ten scrubber groups are defined by us as follows: plate, massive packing, fibrous packing, preformed spray, gas-atomized spray, centrifugal, baffle, impingement and entrainment, mechanically aided, moving bed, and combination. These groups are described and illustrated in detail.

The manufacturers and the trade names of scrubbers in each of the ten categories are tabulated in Chapter 3 of the Handbook. Likewise, patents are tabulated according to the same organization and identified by numer, date, assignee, and a brief comment on the nature of the concept.

HANDBOOK CONTENTS

The Wet Scrubber Handbook contains a wide variety of material pertaining to wet scrubbers. The material covers all aspects of solving a wet scrubber problem, from determining what information is necessary to design a scrubber, through the treatment of liquid and solid wastes coming from the scrubber.

To provide insight into the depth and scope of the material covered in the Handbook, the chapter and major section titles are listed below.

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1.0 Introduction
1.1 Scope
1.2 Approach
1.3 Handbook Format
1.4 Acknowledgements

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2.2 Explore Alternate Solutions
2.3 Decide How to Control the Problem
2.4 General Approach to Scrubbers
2.5 Detailed Considerations
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4.7 Effect of Pressure and Temperature on the Collection of Particles in Wet Scrubbers

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CHAPTER 6 - AUXILIARIES

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CHAPTER 9 - DESIGN EXAMPLES

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CHAPTER 10 - PHYSICAL AND CHEMICAL DATA

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ANALYSIS OF SCRUBBER PRACTICE

As discussed previously, a survey of scrubber users was carried out to define current practice in the application of wet scrubbers to the control of industrial emissions. The results of this survey are presented industry by industry in Chapter Seven of the Handbook.

In the material presented here, generalizations and conclusions based on the data in Chapter Seven are presented. Trends in scrubber application and performance will be pointed out.

Unit Processes to Which Scrubbers are Applied

A unit process is a processing step which is common to several industries. Seven unit processes to which scrubbers are frequently applied are: calciners, fuel burners, crushers, driers, gases, liquid mists and smelters. For example, the scrubbers applied to the calciners used in the lime, cement, and wood pulp industries, can be considered as a group. Similarly, the liquid mist scrubbers used in the sulfuric acid and electroplating industries can also be considered as a group.

The sections below are devoted to the scrubbers applied to the seven unit processes identified above. In the tables, note that the entries in parentheses refer to the number of scrubbers which were available from the survey (Chapter 7) and were analyzed to obtain a datum entry.

Calcining Processes

The industrial processes from which data were extracted and developed for the calcining processes section include: limestone calcining, lime sludge calcining, kraft pulp process recovery furnaces, and cement kilns. All utilize a high temperature gas to chemically alter the material being processed. Only particulate emissions are considered here. The scrubbers used to control calcining processes are described in Table 2.

Venturi scrubbers are most commonly applied to calcining operations, and comprise 70 percent of the scrubbers installed according to the present survey. Simple sprays are also used. The average venturi installation processes less gas, but is more efficient than the average spray. However, venturi systems can also be made to handle large gas flows. Self-induced spray scrubbers are also used. As only three scrubbers of this type were found in the survey, firm conclusions can not be hastily drawn as to their performance.

Combustion Processes

Data for combustion processes were distilled from information on steam boilers used for power generation, and on waste incinerators. Both processes exhaust products of combustion. Table 3 gives this data.

No clear trends emerge. Many different types of scrubbers have been tried - no single type emerges as the definite favorite. An insufficient number of scrubbers have been examined to make definite statements as to efficiency capabilities of various types of scrubbers. It may be noteworthy, however, that the single spray scrubber for which data is available, performed relatively poorly.

Crushers and Mills

Crushers are used to reduce the size of many kinds of ore, stone, as well as finished mineral products. Data on this unit process is given in Table 4 .

Information on the application of scrubbers to crushing processes is spotty. Centrifugal scrubbers were employed in the preponderence of applications surveyed. However, efficiency data are lacking. Any judgments as to typical efficiencies based on the data in Table 4 would be rash.

Driers

Data on fluidized bed, rotary and spray driers are included in Table 5. These devices are used to drive the moisture from minerals, manufactured chemicals and foodstuffs.

Several types of scrubbers have been applied. The most popular is the centrifugal, followed by the venturi and the moving bed. Centrifugal scrubbers are apparently applied to smaller installations than those to which venturi scrubbers are applied. Average efficiency for centrifugal and venturi scrubbers is about equal, as is the highest efficiency encountered. Average and highest efficiencies for the moving bed scrubber are slightly less.

Gases

A wide range of polluting gases can be captured through the application of a suitable scrubber. The data presented in Table 6 reflects the application of scrubbers to the fifteen gases noted on that table.

Almost half of all gas scrubbers are packed towers. Better than a quarter are spray towers. The remaining applications involve every other type of scrubber listed, except for baffle type scrubbers. Packed towers are shown to be capable of high efficiencies. For very large gas flow rates, spray towers and venturi scrubbers have been used.

Liquid Mists

Data on scrubbers used to capture liquid mists come from the acid manufacturing and electroplating industries. These data are given on Table 7.

Packed towers are most frequently used to control liquid mist emissions. They are also apparently the most effective at so doing. Fiber beds and sprays are used for larger installations, and perform with somewhat inferior efficiency.

Smelting

Pyrometallurgical processes supply the data presented in Table 8.

The venturi scrubber is by far the most popular type for the control of pyrometallurgical emissions. It is applied to both very small and very large installations. Efficiency is variable, but has reached high values.

Spray scrubbers have been applied, but are decidedly inferior to other types of scrubber in efficiency in this application. Moving bed scrubbers have displayed good efficiency.

Processes to Which Each Type of Scrubber is Applied

Ten types of scrubbers are used. They differ in layout, efficiency and performance. Their distinguishing layouts are discussed in Chapter 3 of the Handbook, while efficiency and performance are described in Chapter 5 of the Handbook.

Scrubbers are frequently applied to the seven unit processes discussed in the preceeding sections. This section points out those processes to which each type of scrubber is applied, the relative number of scrubbers used in each process, and the overall popularity of each type of scrubber.

The processes to which each type of scrubber is applied are given in Table 14. The data were taken from the survey of scrubber users performed in conjunction with this study, and described in Section 7.2 of the Handbook.

Plate type scrubbers are most frequently applied to drying processes, although they are also applied to combustion and smelting processes, and for pollutant gas removal.

Fiber bed scrubbers, like packed towers, are used to capture pollutant gases and liquid mists.

Spray chambers are used to capture gases. They are also applied to smelting operations (wet caps) and very occasionally to calcining, combustion, drying processes, and for the collection of liquid mists.

Venturi scrubbers are used most frequently on smelting operations. They are also used on calcining and drying processes, and occasionally for pollutant gas collection and for control of combustion processes.

Most centrifugal scrubbers are applied to driers. Some are applied to crushing. Centrifugal scrubbers are seldom used to control processes other than these.

Baffle scrubbers have rarely been used. The only application uncovered in the users survey was to a drying process.

Self-induced spray scrubbers are applied to calcining, combustion and crushing processes, and for pollutant gas collection.

Few applications of mechanically aided scrubbers were uncovered in the users survey. Those applications noted were to drying and smelting processes, and for pollutant gas removal.

Moving bed scrubbers are applied most frequently to drying processes. They are also used to control smelting and combustion processes, and for the control of crushers and polluting gases.

Sales of Scrubbers Compared With Other Equipment

Other types of control equipment than scrubbers are often used on the processes which have been discussed in the preceeding sections. Table 9 lists the sales in 1967 of all types of air pollution control equipment. This table is adapted from "Industrial Gas Cleaning Equipment Shipments and End Use - 1967", prepared by the U. S. Department of Commerce, Washington, D.C. 20230 (10¢). The figures given are for uninstalled equipment.

TABLE 2

SCRUBBERS USED TO CONTROL PARTICULATE EMISSIONS FROM CALCINING PROCESSES+

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(1) 3	(1) 3	(0) 0	(5) 15	(23) 70	(0) 0	(0) 0	(3) 9	(0) 0	(0) 0	(33) 100
Through-put, (m^3/hr)	Low	-	-	-	270	510	-	-	1700	-	-	
	Avg.	(1) 1700	(1) 1700	-	(5) 103,600	(20) 49,400	-	-	(3) 77,200	-	-	
	High	-	-	-	220,000	159,000	-	-	115,000	-	-	
Effic-iency (%)	Low	-	-	-	85	87.4	-	-	96	-	-	
	Avg.	(1) 55	(1) 70	-	(4) 93.5	(20) 95.1	-	-	(3) 96.7	-	-	
	High	-	-	-	98	99.7	-	-	98	-	-	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

+Includes:
- Limestone Calcining
- Lime Sludge Calcining
- Kraft Pulp Process Recovery Furnace
- Cement Kilns

TABLE 3

SCRUBBERS USED TO CONTROL PARTICULATE EMISSIONS FROM COMBUSTION PROCESSES+

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(3) 25	(0) 0	(0) 0	(2) 17	(2) 17	(1) 8	(0) 0	(2) 17	(0) 0	(2) 17	(12) 101
Through-put, (m^3/hr)	Low	255	-	-	-	3400	-	-	1800	-	1340	
	Avg.	(3) 2390	-	-	(1) 327,000	(2) 1,265,000	(1) 51,300	-	(2) 2000	-	(2) 425,000	
	High	5400	-	-	-	2,530,000	-	-	2200	-	850,000	
Effic-iency (%)	Low	27.8	-	-	-	95	-	-	-	-	99	
	Avg.	(3) 72.5	-	-	(1) 29	(2) 97.3	(1) 99	-	(1) 90	-	(2) 99.3	
	High	99	-	-	-	99.7	-	-	-	-	99.6	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey

+Includes:

Power generation boilers
Waste incinerators

TABLE 4

SCRUBBERS USED TO CONTROL PARTICULATE EMISSIONS FROM CRUSHERS AND MILLS+

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(1) 7	(0) 0	(0) 0	(0) 0	(0) 0	(11) 79	(0) 0	(1) 7	(0) 0	(1) 7	(14) 100
Through-put, (m^3/hr)	Low	-	-	-	-	-	8500	-	-	-	-	
	Avg.	(1) 30,000	-	-	-	-	(11) 43,000	-	(1) 16,100	-	(1) 4250	
	High	-	-	-	-	-	110,000	-	-	-	-	
Efficiency (%)	Low	-	-	-	-	-	-	-	-	-	-	
	Avg.	-	-	-	-	-	(1) 99.9	-	(1) 95	-	(1) 98.7	
	High	-	-	-	-	-	-	-	-	-	-	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

+Includes:

Ore crushing
Stone crushing
Phosphate rock crushing

TABLE 5

SCRUBBERS USED TO CONTROL PARTICULATE EMISSIONS FROM DRIERS+

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(7) 9	(0) 0	(0) 0	(4) 5	(19) 25	(30) 40	(1) 1	(0) 0	(1) 1	(14) 19	(75) 100
Through-put,	Low	71,500	-	-	21,800	37,400	8500	-	-	-	4250	
	Avg.	(7) 202,000	-	-	(4) 32,000	(13) 150,000	(29) 54,100	(1) 102,000	-	(1) 17,000	(14) 37,100	
(m^3/hr)	High	340,000	-	-	42,500	344,000	119,000	-	-	-	100,000	
Effic-iency	Low	-	-	-	85	91	81	-	-	-	89.7	
	Avg.	-	-	-	(3) 94	(8) 97.8	(17) 97.4	-	-	(1) 99	(12) 96.5	
(%)	High	-	-	-	99	99.7	99.7	-	-	-	98.8	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

+Includes:
Fluidized Bed Driers
Rotary Driers
Spray Driers

TABLE 6
SCRUBBERS USED TO CONTROL GASES+

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(3) 4	(33) 46	(2) 3	(18) 30	(10) 14	(1) 1	(0) 0	(1) 1	(2) 3	(1) 1	(71) 102
Through-put, (m^3/hr)	Low	2230	17	4250	42	142	-	-	-	-	-	
	Avg.	(3) 31,400	(32) 8600	(2) 87,000	(17) 34,500	(9) 36,600	(1) 42,500	-	(1) 6800	(1) 1450	(1) 1340	
	High	48,000	51,000	170,000	170,000	170,000	-	-	-	-	-	
Efficiency (%)	Low	71	70	92	89	70	-	-	-	57	-	
	Avg.	(3) 87	(26) 94.6	(2) 94.3	(12) 93.7	(8) 90	(1) 99.8	-	(1) 36	(2) 73	(1) 82	
	High	96.7	99.9	96.7	99.8	99.7	-	-	-	90	-	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

+Includes:
H_2O
Acrylic monomers
Formaldehyde
HF
N_2O_4
HCl
odors
H_2S
NH_4OH
NH_3
Cl_2
SiF_4
SO_x
Cl_2
I_2

TABLE 7

SCRUBBERS USED TO CONTROL LIQUID MISTS[+]

		Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri-fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used		(0) 0	(11) 65	(3) 18	(3) 18	(0) 0	(0) 0	(0) 0	(0) 0	(0) 0	(0) 0	(17) 101
Through-put, (m^3/hr)	Low	-	2040	3400	25,200	-	-	-	-	-	-	
	Avg.	-	(10) 35,600	(3) 54,200	(3) 45,000	-	-	-	-	-	-	
	High	-	85,000	156,000	85,000	-	-	-	-	-	-	
Effic-iency (%)	Low	-	50	78	51	-	-	-	-	-	-	
	Avg.	-	(8) 86.6	(3) 83.3	(2) 70	-	-	-	-	-	-	
	High	-	99.3	88	90	-	-	-	-	-	-	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

[+] Includes:
Chromic acid
Sulfuric acid
Nitric acid
Hydrochloric acid

TABLE 8

SCRUBBERS USED TO CONTROL PARTICULATE EMISSIONS FROM SMELTING OPERATIONS+

	Plate	Packed Tower	Fiber Bed	Spray	Venturi	Centri- fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed	Total
% each type used	(3) 4	(1) 1	(0) 0	(8) 11	(54) 76	(0) 0	(0) 0	(0) 0	(1) 1	(4) 6	(71) 99
Through- put, (m³/hr) Low	52,400	-	-	68	500	-	-	-	-	34,000	
Avg.	(2) 98,000	(1) 8150	-	(3) 20,400	(51) 73,700	-	-	-	(1) 8500	(4) 54,500	
High	143000	-	-	41,300	400,000	-	-	-	-	85,000	
Effic- iency (%) Low	91	-	-	68	72.5	-	-	-	-	95	
Avg.	(2) 93	-	-	(2) 83	(41) 95.5	-	-	-	(1) 95	(3) 98.7	
High	95	-	-	97.5	99.7	-	-	-	-	99	

Notes: Numbers in parentheses refer to number of scrubbers analysed to obtain data entry.

Low and High values are lowest and highest values found in the scrubber survey.

+Includes:
Blast Furnaces
Steel Furnaces
Iron Foundries
Ferroalloy Furnaces
Copper Smelting
Aluminum Smelting
Nonferrous Reclaimation Smelting

TABLE 9

INDUSTRIAL GAS CLEANING EQUIPMENT - MANUFACTURER'S SHIPMENTS BY INDUSTRY, 1967

(Purchase Price in Thousands of Dollars)

Industry	Total Shipments	Adsorbers & Incinerators	Electrost. Precip.	Fabric Filters	Mech. (Cyclone) Collec.	Scrubbers	
						Gases	Particles
Iron & Steel	24,317	(2)	5,783	4,536	2,300	4,275	7,423
Utilities	18,481	(1)	15,506	(1)	2,476	(1)	(1)
Chemicals	15,870	1,001	1,207	5,344	3,130	1,479	3,704
Rock Products	8,966	(1)	2,760	3,602	1,038	(1)	1,142
Pulp & Paper	6,753	(1)	(1)	122	802	193	989
Mining & Metal-lurgical	6,160	(1)	(1)	1,855	389	394	825
Refinery	4,098	282	(1)	(1)	(1)	(1)	(1)
All Clear$^{(4)}$	20,206	2,137	687	4,959	8,408	114	3,901
Exports	5,744	79	(1)	1,081	(1)	72	651
Totals	110,595	3,976	36,509	21,730	22,381	6,770	19,229

Notes:
(1) Not published to avoid disclosure.
(2) Gas incinerators and absorbers purchased by iron & steel companies are included in "all others" category to avoid disclosure.
(3) "Rock Products" includes cement & asbestos.
(4) "ALL other" includes shipments to distributors where end use cannot be identified.

OTHER AREAS OF APPLICATION

Scrubbers are used in a wide variety of applications, as the preceeding section shows. Yet there are many situations in which they are not used or are little used, and the question comes to mind; whether this is as it should be.

The choice of any air pollution control device depends on a number of factors. Obviously, the performance must be adequate to the needs and the system must fit within any other constraints that exist. Given that the system can do the job, the big question is: "What will it cost, both for investment and operation?"

Ideally, the questions of performance and cost are correctly dealt with. Actually, there are many instances in which the correct decision was not made. Sometimes the problem itself is not properly defined so that the particulate loading or size, or gas composition, or flow rate, or other factors are not known with adequate accuracy. Additionally, there are cases where the control device performance and cost characteristics were not known or where a suitable alternative was not considered.

In an effort to ensure that worth-while opportunities for the further exploitation of scrubbers are not overlooked, some effort has been directed to the search for such prospects.

Potential Applications

As we search for potential applications there are some general ideas about which situations would be positive and negative in terms of possibilities. First, to list the conditions under which new or increased application is possible, we can identify them as where:

1. Performance requirements change so that alternatives should be re-evaluated. Often this occurs when A.P.C. (air pollution control) laws become more restrictive and require greater efficiency of control or the control of gases as well as particulates. Sometimes the source process or materials change so as to change the nature of the effluent.

2. Scrubbers improve. The decision to use one type of A.P.C. equipment may have been made a number of years ago and it has not been re-examined in the light of new developments.

3. Scrubber systems get cheaper. Compared to capital and/or operating costs for other systems scrubber costs may be competitive in applications where this was not previously the case.

4. Accessory problems can now be solved satisfactorily. A number of auxiliary equipment or process problems such

as fan corrosion or cost, liquid treatment, stack corrosion, entrainment separation, and waste disposal might now be economically resolved.

5. Scrubbers never were that bad. People have a tendency to remember only a few simple "facts" and have, in some cases, been misinformed about scrubbers.

6. They never thought of using one. Decisions to install A.P.C. equipment are sometimes made by non-technical people, or even technical people, who simply never considered the possibility of using a scrubber and perhaps never heard of them.

Negative Factors

While we are reluctant to state that anything is impossible, there are situations where it is quite unlikely that a scrubber would be a good choice. Some factors which would exert a negative influence on the choice of a scrubber are where:

1. Liquid is not economically available. For mass transfer this means that a suitable solvent either is not known or is too expensive. For particle collection it may simply mean that even water is not available.

2. Liquid recycle or waste disposal are not economical or possible. If cleanup of the scrubber effluent liquid is not possible or worth doing, there comes a point where a liquid effluent must be discharged and this may not be possible.

3. Space not available. Scrubbers do require a significant amount of space (although not as much as some other devices) and for some applications the total requirements on performance-space-power may make another device clearly superior.

4. High efficiency on about 0.5μm diameter particles is required. This is the "low spot" in scrubber performance within present technology, although possibilities exist for overcoming it in some cases.

5. Low or moderate efficiency will suffice. If the particle size is large, a mechanical collector may be the much simpler and cheaper way to get the necessary performance.

6. Corrosion is severe for wet scrubbers. In some cases, the dry gas is much less corrosive than when water is present.

7. High temperature must be maintained. Although molten salts and high-boiling organic liquids have been used for some applications, it may be that a suitable liquid and liquid handling system are not known or economical for others.

8. Collected dust or gas is re-used and is deteriorated by liquid contact. In cases where the effluent can be returned to the process or sold as product, it might be prohibitively expensive to recover it from scrubber liquid as compared to a dry A.P.C. system.

9. Complexity can not be tolerated. When the time or opportunity for maintenance is severely limited or when the operating labor is not competent, a scrubber might require too much attention.

10. Operating cost is more important than investment. Depending on the capital position, management policy, and complexities such as taxes, it might be more desirable for a company to spend more on the initial investment and less on operating cost than a scrubber would require.

Survey of Potential

The major method of finding new applications for scrubbers is to look for situations in which they have not been used and where "the competition" has been selling equipment. Surveys by APT and others (MRI, "Particulate Systems Handbook", 1970; SRI, "Electrostatic Precipitation Handbook", 1970; GCA, "Fabric Filter Handbook", 1970; and NAPCA, "Control Techniques for Particulate Air Pollutants", 1969) are good sources of this kind of information.

The NAPCA (1969) document presents a tabulation of data on the use of particulate collectors by industry, which is reproduced in Table 10. We have added the column labeled "More W.S." to indicate possible new applications for wet scrubbers. They are generally those for which scrubbers are not now used to any significant extent. While we have considered the question of whether required performance could be obtained, we have not computed costs to establish economic feasibility. The economics are so complex as to preclude any broad generalization and must be evaluated for each specific case.

The APT surveys of scrubber users and manufacturers have yielded some generalizations on scrubber use as shown in the previous section of this report. Some leads as to potential applications have been extracted from that material.

The processes covered are calcining, chemical, food and feed, metallurgical, and combustion. Table 11 lists processes where scrubber application potential exists, and the characteristics of the emissions these scrubbers will have to control.

TABLE 10

USE OF PARTICULATE COLLECTORS BY INDUSTRY

Industrial Classification	Process	EP	MC	FF	WS	Other	More W.S.
Utilities & industrial power plants	Coal	0	0	--	--	--	X
	Oil	0	0	--	--	--	X
	Natural Gas	--	--	--	--	--	--
	Lignite	0	0	--	--	--	X
	Wood and Bark	+	0	--	+	--	--
	Bagasse	--	0	--	--	--	X
	Fluid Coke	0	+	--	--	+	X
Pulp and Paper	Kraft	0	--	--	0	--	--
	Soda	0	--	--	0	--	--
	Lime Kiln	--	--	--	0	--	--
	Chemical	--	--	--	0	--	--
	Dissolver tank vents	--	0	--	--	+	X
Rock Products	Cement	0	0	0	+	--	X
	Phosphate	0	0	0	0	--	--
	Gypsum	0	0	0	0	--	--
	Alumina	0	0	0	+	--	X
	Lime	0	0	+	--	--	X
	Bauxite	0	0	--	--	--	X
Steel	Magnes.Oxide	+	+	--	--	--	X
	Blast Furnace	0	--	--	0	+	--
	Open hearth	0	--	--	+	+	X
	Basic oxygen furnace	0	--	--	0	--	--
	Electric.Furnace	+	--	0	0	--	--
	Sintering	0	0	--	--	--	--
	Coke Ovens	0	--	--	--	+	?
	Ore Roasters	0	0	--	+	--	X
	Cupola	+	--	+	0	--	--
	Pyrites roaster	0	0	--	0	--	--
	Taconite	+	0	--	--	--	X
	Hot scarfing	0	--	--	+	--	X
Mining and Metallurgical	Zinc roaster	0	0	--	--	--	?
	Zinc smelter	0	--	--	--	--	X
	Copper roaster	0	0	--	--	--	X
	Copper reverb	0	--	--	--	--	X
	Copper converter	0	--	--	--	--	--
	Lead furnace	--	--	0	0	--	--
	Aluminum	0	--	--	0	+	--
	Elemental Phos.	0	--	--	--	--	--
	Ilmenite	0	0	--	--	--	X
	Titanium dioxide	+	--	0	--	--	X
	Molybdenum	+	--	--	--	--	X

TABLE 10 (cont'd)

USE OF PARTICULATE COLLECTORS BY INDUSTRY

Industrial Classification	Process	EP	MC	FF	WS	Other	More W.S.
Mining & Metallurgical (continued)							
	Sulfuric acid	0	--	--	0	0	--
	Phosphoric acid	--	--	--	0	0	--
	Nitric acid	--	--	--	0	0	--
Miscellaneous	Ore beneficiation	+	+	+	+	+	--
	Refinery catalyst	0	0	--	--	--	X
	Coal drying	--	0	--	--	--	X
	Coal mill vents	--	+	0	--	--	X
	Municipal incin.	+	0	--	0	+	--
	Carbon black	+	+	+	--	--	--
	Apartment incin.	+	+	+	--	--	?
	Spray drying	--	--	--	0	--	--
	Machining operation	--	0	0	+	+	X
	Hot coating	--	--	--	0	0	--
	Precious metal	0	--	0	--	--	X
	Feed and Flour milling	--	0	0	--	--	X
	Lumber mills	--	0	--	--	--	?
	Wood working	--	0	0	--	--	

Key:

0=Most Common
+=Not normally used
EP=Electrostatic Predipitator
MC=Mechanical Collector
FF=Fabric filter
WS=Wet scrubber

Other=Packed towers
Mist pads
Slag filter
Centrifugal exhausters
Flame incineration
Settling chamber

X = likely
? = possibly

TABLE 11

PROCESSES WITH SCRUBBER APPLICATION POTENTIAL

Process	Emission Small Particles	 Inorganic Gases	Odors
Calcining Processes			
Cement manufacturing	x	?	
Frit manufacturing	x		
Glass manufacturing	x		
Rock wool manufacturing	x		
Chemical Processes			
Calcium carbide mfg.	x	x	
Starch manufacturing	x		
Soap & detergent mfg.	x		x
Resin manufacturing	x	?	?
Food & Feed Processes			
Coffee roasting			x
Fish meal processing			x
Meat & fish packing			x
Combustion Processes	x	x	
Metallurgical Processes			
Copper smelting	x	x	
Lead smelting	x	x	
Zinc smelting	x	x	
Metal melting in cupolas	x	?	

Calcining Processes

Calcining processes use high temperatures to fuse or chemically alter a mineral feed material into a finished product. Usually calcining produces significant quantities of sub-micron particles. These particles are usually collected in an electrostatic precipitator or fabric filter system. The relatively high concentration and submicron size of the dust emission from calcining processes make scrubber applications economically unattractive due to the high energy requirements necessary for efficient particle removal. However, scrubbers would find significant application if a way is found to reduce the energy requirements of suitably efficient scrubbers.

Specific calcining processes which would have expanded use for scrubbers include: cement, frit, glass, and rock wool manufacturing.

Chemical Processes

Chemical processes convert feed materials into product through one or more chemical reactions. Particles, (or mists), polluting gases, or sometimes both, are emitted.

Scrubbers can find additional use on chemical processes where legislation forces the control of presently uncontrolled gaseous emissions. Mist and particle emissions may also be controlled with scrubbers.

Chemical processes which may provide additional applications for scrubbers include: calcium carbide, starch, soap and detergent, and resin manufacturing facilities.

Food and Feed Processes

The processing of edible materials often produces odors and/or dusts. Odors arise whether the process material is vegetable or animal in nature. Dusts come primarily from grain handling facilities.

To eliminate nuisance or to satisfy odor emission laws, scrubbers can be used. Tightening laws and increased citizen complaints will necessitate controlling odorous emissions from food and feed processes which are presently uncontrolled.

Processes to which additional scrubbers may be applied in the food and feed industry include: coffee roasting, fish meal processing, and fish canning industries among others.

Metallurgical Processes

Scrubbers are already widely used for the control of emissions from metallurgical processes. Additional scrubber applications will be necessary to control the copious gaseous emissions evolved in smelting operations, particularly in the smelting of nonferrous sulfide ores such as copper, lead and zinc sulfides. The sulfides are driven off as SO_2, and are for the most part presently uncontrolled.

In some plants, the concentration of SO_2 in the smelter exhaust gases may be sufficiently high to serve as a feed stream to a contact sulfuric acid plant. In many cases, however, it is more economical to scrub the sulfur oxides from the emitted gases, without attempting further process stages to convert them to a salable product.

Combustion Processes

Stationary combustion processes have used scrubbers to a limited extent for the control of particulate matter. More common control techniques have involved multi-cyclones, often followed by electrostatic precipitators.

Tightened control regulations on the emission of polluting gases will widely extend the application of scrubbers to the control of these gases. The only viable alternative to the use of scrubbers for the removal of sulfur oxides is the use of a low sulfur fuel. In many cases, unavailability or high prices of low sulfur fuels will force scrubbers to be used, as they are then the only available way to achieve the required levels of air pollutant control.

Conclusions

Changing technology and emission regulations may lead to the future application of scrubbers to pollution control problems where scrubbers are not widely applied now. The most promising areas are for the cleanup of submicron particles and for inorganic gases. Additional scrubber applications for the removal of submicron particles will require the development of scrubbers capable of removing these particles with good efficiency without developing the high operating costs (due to high energy comsumption) presently needed. Additional applications for inorganic gas scrubbing will require tightened and enforced regulations on the emissions of these gases.

Despite increased competition from rival means of pollution control, trends in scrubber technology development and emission standards indicate that the application of scrubbers will most likely increase in the future.

Three possible methods for increasing scrubber performance on submicron particles, particle growth, hydrophilizing, and utilizing flux (-phoresis) forces, show promise but need to be proven. Proving one or more of these methods may increase scrubber applications in this area. Regulations on the emission of inorganic gases are tightening and more scrubbers will be used to meet these regulations.

RESEARCH AND DEVELOPMENT PLAN

Wet scrubbers are simple devices demanding relatively low capital cost and able to remove particulate and gaseous contaminants simultaneously. This is the reason for their growing role in air pollution control. However, like most simple devices, wet scrubbers require good understanding of the principles and processes involved, for best performance. In many cases we have found that scrubbers do not perform to capacity because of lack of understanding of the basic operating mechanisms and that much improvement in efficiency can be achieved through simple and relatively inexpensive changes.

A major disadvantage of scrubbers as presently used is their poor performance in collecting small particles in the size range of 0.1-2μm in diameter. This weakness is due on one hand to the decrease in the inertial collection mechanism, which is the major collection mechanism for particles larger than ≈1μm in diameter. On the other hand, the diffusional mechanism, which is responsible for the collection of smaller particles, is not significant for particles larger than ≈0.1μm. The 0.1-2μm range of particle sizes is an important one, because these particles have the highest degree of respiratory system penetration and retention, and thus have the largest effect on human health. Particles in this size range also have a high light scattering coefficient. Accordingly, this class of particles is mainly responsible for the degradation of visibility in the atmosphere. Furthermore, heat absorption by small particles is closely related to scattering, so that fine particles will have an important effect on the earth's heat balance and climate.

When one studies the available literature relevant to wet scrubbers, one always finds the need for more experimental work to support much of the theoretical studies already carried out. There is need for research to verify and further develop theories and basic concepts, as well as equipment and better engineering methods for equipment design. The need exists for more basic data on scrubbing systems and for trial of new systems. One finds that many empirical equations which are used successfully in equipment design, cover only a short range of operating conditions and thus undermine any effort to change traditional designs and optimize equipment performance. In general, there is a need for a large and comprehensive research program in all phases of scrubber science and technology, to better avail this simple and versatile class of air pollution control equipment for general and efficient use.

In this chapter we have compiled and classified research needs under the following sub-headings:

1. Basic concepts.
2. Physico chemical data.

3. New equipment.
4. Engineering design and optimization.
5. Dynamic behavior, and control equipment and techniques.

Two five-years research plans are suggested following the discussion of the various needs.

Basic Concepts

Collection efficiency by many unit mechanisms, based on collection element crossectional area, can be increased above 100% (for the individual collection element), if forces, in addition to inertia and diffusion, are applied. Such effects due to diffusiophoretic, thermophoretic, electrostatic and magnetic forces has been known for years. Theories and equations describing these forces are found in the literature, but good reliable experimental data, to verify these theories, are meager. The thermophoretic and diffusiophoretic forces have further advantage in that they are independent of particle size in the important range of particle diameters 0.1-2μm. To break the 100% efficiency limit, and to increase collection of fine particles, further study of these basic phenomena and their incorporation in air pollution control devices is needed.

As noted earlier, the combination of diffusion and inertia mechanisms shows a minimum collection efficiency in the 0.1μm-2μm diameter range. By increaseing particle size, one can get away from this range and increase collection. More studies are needed of the basic phenomena leading to fast particle growth due to condensation and chemical reaction, and in the presence of various force fields such as: sonic, electrostatic, thermal and aerodynamic.

A special case of aerodynamic force which received much attention lately is turbulent agglomeration. The rate of turbulent agglomeration increases in proportion to the radius cubed of the larger particles involved. Calculations based on theoretical equations failed to show the importance of this mechanism for particles smaller than 4μm in diameter. However, experimental evidence to support the theoretical equations are missing. A basic study to determine the actual relationship, range of application and magnitude of turbulent agglomeration is required.

Another promising collection mechanism, is the inertial collection of small particles (d_p<1μm) by the back of spheres at high Reynolds number. It was shown by Goldshmid and Calvert (1963) that at high Reynolds numbers, vortices are formed and particles smaller than ≈1μm in diameter are deposited by centrifugal forces on the back of the collector. This may be a way to increase collection at this low efficiency range of particle sizes.

Most of the collection equations for different shape obstacles have been solved for two extreme flow conditions, namely: potential and viscous flow. However, reliable interpolation equations for other flow conditions are missing. Studies should be carried out to determine collection efficiency of particles by different shape collectors at various Reynolds numbers.

An assumption usually made in theoretical calculations is that every particle which hits the collecting body sticks to it. There is enough experimental evidence to weaken this assumption, especially in the case of particles which are not wetted by the collector's liquid. There is a need to study what happens to a particle after it hits the drop surface and what are the conditions which most effect its capture. Such studies may lead to increased collection efficiencies by preconditioning the collecting liquid and the aerosol particles. Examples are the addition of surfactants to change liquid surface properties or the dispersal of NaCl aerosol to make the collected aerosol more hygroscopic.

A corollary study would be the study of reentrainment. How are collected particles reentrained? What is the magnitude of particle reentrainment and how can reentrainment be reduced?

Mass transfer to slurries with chemical reaction, such as limestone slurry for SO_2 scrubbing, requires more study. The inclusion of particulate matter in slurries permits more reacting material to be included in the scrubbing solution than is attainable when pure solution is used. However, the rate of solution of the particulate matter may become controlling, eliminating some of the advantage gained by the larger reservoir of reactant. From the available literature it is clear that more basic research is needed to understand the various aspects of mass transfer to slurries.

There is a need for a thorough study of the effect of liquid phase turbulence on the overall mass transfer coefficients, in a dispersed gas in a liquid system. Available work is relatively limited in scope and additional experimental work of broader scope, more fundamental nature and with a unified approach is needed.

For most devices used in wet scrubbing operations, the design procedure is on much firmer grounds if the area available for mass transfer and particle collection is known. Additional basic research on interfacial areas in scrubbing devices would be beneficial to the scrubber designer. This study should be primarily experimental.

Physico-Chemical Data

The use of solutions and slurries which react with the gaseous contaminant is often preferable to the use of pure water. In many cases the kinetic data available are so meager that it is difficult to evaluate or design the scrubber. More kinetic and equilibrium data are needed for reactions common to wet scrubbers.

Reversible reactions which permit the recovery of the contaminant and the absorbing liquid under different operating conditions, should be studied. A start can be seen in the vast research studies carried out by various institutes for better absorbing solutions for SO_2 removal. Reactions which promise better and faster removal of contaminants should be studied with the ultimate being the recovery of the contaminant and absorbing liquid.

Reliable values of diffusivities in the gas and in the liquid phase are essential if mass transfer performance is to be predicted and correlated from fundamental relationships rather than completely empirically. However, experimental diffusivities are unavailable in the literature for a large proportion of the gaseous components of interest in industrial wet scrubbing applications. The values given in Chapter 10 of the Handbook for both gaseous and liquid diffusivities are estimated in most cases, and the best estimation techniques are only approximate for many of the most important compounds, particularly polar and/or electrolytic molecules in water. High priority should be given to measuring diffusivities of industrial gaseous pollutants in air and in water, at least over the temperature range of 20°C-90°C for water, and up to at least 150°C for air. The concentration range could be limited to relatively dilute levels for scrubbing applications.

Research should also be aimed at better understanding of liquid phase mass transfer coefficient, especially with chemical reactions. An experimental program sould be undertaken to fill the gap in known "k_L" data, for applicable unit mechanisms, using the actual gaseous components of interest in industrial air pollution problems. This approach could also be employed in particle collection by diffusion, and data from the previous paragraph, regarding the transfer of caught particles into the interior of the drop, could be used for determining some sort of particulate "k_L".

New Equipment

The results of the basic research projects, mentioned in the last two sections, would lead to the design of improved, more efficient, and more economic wet scrubbers incorporating those ideas. Compact scrubbers with high removal efficiencies for fine particles and gaseous contaminants, incorporating particle growth and additional force fields, are the next scrubber generation. Such scrubber systems will require a fresh look since addition of flux forces, or particle growth, to existing devices will not yield optimum results. As an example, the new scrubber generation using thermophoresis should be designed to preserve temperature gradient rather than to increase heat transfer.

The new generation of scrubber systems will distinguish itself from the present generation by:

1. Utilizing additional forces.
2. Building up particles.
3. Compactness, i.e. the whole system will operate at much higher gas velocities.
4. Specificity, i.e. designed specifically for the purpose of particle collecting together with increased mass transfer. Future scrubbers may have different designs for different industries.
5. Changing liquid and particulate properties to increase collection efficiency.

Entrainment separators are an essential part of the wet scrubber system. In many cases, especially when coupled with venturi scrubbers, entrainment separators are the main cause of the large physical dimension of the system. The design of a compact and efficient entrainment separator is a prerequisite for compact scrubber systems. Work should be started by reviewing the field of entrainment separators and developing new and compact units.

Additional advantage could be achieved by matching scrubbers and sources. This study will determine what kind of scrubber is best suited for specific emission sources, such as power plants, cupolas, chlorine manufacturing plants, incinerators, odor control, etc. Special attention should be paid to the data obtained through reserach on topics mentioned in the last paragraph. For example, we should seek new systems employing different liquids or slurries which will react rapidly with the contaminant and remove it totally from the gas, liquids that have better equilibrium and collection properties.

There is frequently insufficient information on the applicability and suitability of newer plastics and composite materials for scrubber systems. A material evaluation program to compare the corrosion properties of various materials could lead to significant saving in scrubber construction costs.

When improving equipment performance, clogging difficulties should also be examined. There is a need to develop methods and accessories to avoid plugging and clogging of spray nozzles, packed columns, sieve plates, fibrous packing and secondary flow scrubbers.

The equations we have studied point out that better collection efficiencies, especially for the critical particle size range of 0.1μm - 1μm diameter, could be achieved by operating at a partial vacuum. The economics of vacuum scrubbers should be studied.

Engineering Design and Optimization of Scrubber Systems

A standard method of evaluating and reporting wet scrubbers performance is needed. The data in equipment manufacturer's brochures are often not reliable, or do not tell the exact story. Many manufacturers use hygroscopic particles, whch grow and change shape in the equipment, to evaluate scrubber performance. This kind of information, if used by a design engineer for non-hygroscopic particles, will lead to equipment with poor actual performance. In other cases, manufacturers do not specify and underline that the gas has to be saturated with water vapor to obtain the claimed efficiencies. A standard method for testing and reporting scrubber performance data should be complimented with calculation methods showing how to predict actual collection efficiencies for specific cases from the measured data.

It would be very advantageous to establish and maintain an independent scrubber testing facility to determine performance under a large variety of contaminants and operating conditions and confirm or refute claimed efficiencies. Such a facility, which resembles the underwriter's laboratory, would give an independent and reliable scale for comparison of various scrubbers. In time the facility can be enlarged to compare various methods of air pollutants control on an even basis, thus performing a valuable service and helping decisions in border cases. Such a testing facility will also help in separating scrubber engineering from scrubber manufacturing. It will permit independent engineers to acquire operational data, which to a large extent is now held as proprietary information by the scrubber manufacturers.

Equations or correlations are needed for predicting collection efficiency when several mechanisms contribute simultaneously to particle collection. For example, this could be done for the simultaneous action of inertia, thermophoresis and electrostatic forces by numerically solving the equation of motion with all these forces included.

Collection of hygroscopic and hydrophilic particles is easier than hydrophobic particles. There is need for a calculation method that will convert collection efficiency data from hygroscopic to non-hygroscopic particles and vice versa.

During our study we found that many empirical design equations which are used extensively by air pollution engineers are correct only within a narrow range of operating conditions. The fact that these equations were never questioned stems from designers attitude not to question successful designs of already operating equipment. If one wants to optimize collection equipment for better performance and lower operating costs, more reliable collection efficiency and pressure drop equations, covering a wider range of operating conditions, are needed.

Optimization of not only scrubbers, but scrubber systems would be profitable. This can be done by studying various combinations of different devices for particle collection, mass transfer, particle growing, etc. It seems that optimum systems could be best designed for specific sources. Thus studies should be carried out to yield the optimum scrubber system design for a contaminant source.

Equations for calculating and predicting equipment performance should be backed up by a massive field study. One should not expect it to be done by equipment users or equipment manufacturers. This survey of actual operating conditions will include: pressure drop, liquid and gas flow rates, collection efficiency, particle size distribution, mass transfer, and operating conditions, and should be carried out by an independent body, preferably the laboratory mentioned previously, using approved measuring techniques.

The design methods given in the "Wet Scrubber Handbook" utilize the unit mechanism approach. We feel there must be a thorough experimental verification of these equations. The need is especially acute where the equations derived from basic principles are applied to equipment like centrifugal scrubbers, co-current spray chambers, etc., where much of the actual operating data collected are not dependable and comprehensive.

Dynamic Behavior and Control Instrumentation Technique

There is much need for on-line instruments to measure continuously the performance of wet scrubbers, such as a simple and cheap instrument to measure continuously particle mass concentration. This instrument will indicate continuously the scrubbing efficiency and the mass of particulate discharged into the atmosphere. Parallel instrument or instruments that measure concentration of gaseous contaminants, like NO_x, SO_x, etc., is also needed.

The dynamic response of scrubber systems to upsets has not been studied extensively. The behavior of a system during start-up and shut-down and more particularly, the response of a scrubber system to overload surges, is important to its proper design and operation. Since many operating scrubbers experience upsets, a program of theoretical models, derived from and subsequently verified by data from operating installations, could provide valuable design data.

Criteria for the Preparation for a Five-Year Research Plan

Wet scrubbers have definite areas of strength and weakness. We feel that when assigning priorities, two criteria should be used. The more important one is, that pressing air pollution problems have first priority, and the second criteria is that scrubbers should be applied in their areas of strength.

The pressing problems of highest priority are auto exhaust and power plants emission. We do not now see the application of scrubbers to combat auto exhaust, however we think along this line. With power plants emission the story is different. There the need exists to control gaseous and particulate contaminants simultaneously. This is one of the strong areas of wet scrubbers as air pollution control equipment. For successful application of scrubbers to power plant emission control, two basic studies are needed. One is to find the best and most economical scrubbing process (to distinguish from equipment). The second is to increase scrubber range of operation so as to obtain simultaneous absorption of gaseous contaminants, mainly SO_2, and efficient collection of a wide range of particle sizes, mainly fine particles. The development of better processes and more sophisticated hardware will eventually reduce overall capital and operational costs.

Many studies are carried out now to define a process for power plant flue gas purification, but the area of fine particles control through scrubbers has been neglected. That is why we consider the study of condensation scrubbers to be of the highest priority.

Often scrubbing equipment for both mass transfer and particulate removal from gases appear to be of large physical dimensions relative to the volume of gas treated. A step in the right direction toward compactness was the introduction of high gas velocity equipment such as the venturi scrubber. However, the high gas velocity equipment is usually coupled to a low velocity entrainment separator. Thus, the study and development of a high gas velocity entrainment separator that will simultaneously solve many of the other problems which plague entrainment separators, will contribute to the compactness and efficiency of scrubbing systems.

Much confusion exists in defining the problem and specifying desired equipment performance. This confusion continues through all the stages of contract writing and later in the evaluation of the new equipment performance. It is also reflected in brochures of various scrubber manufacturers. The need exists for a standard method of specifying and evaluating equipment performance.

There are very few good data on actual field performance of various scrubbers, and its variation with time and industry. If we would like future equipment to perform to specifications, this program should be given a high priority.

In many cases control equipment of one type is not the optimal answer, in other cases tradition often dictates the type of equipment used. That is the reason for the high priority assigned to the study of matching: industry and control equipment. We are sure that many interesting results will come out of this study.

Based on the criteria mentioned earlier, two five-year research plans are presented in Tables 13 & 14. Table 13 assumes a total expenditure of two million dollars while Table 14 assumes an expenditure of 6.3 million dollars in five years. It is recommended that the additional 0.7 million dollars required to make Plan B a seven million dollar plan be used for demonstration grants, to demonstrate performance of the second generation scrubbers under actual plant conditions.

Both tables list the various research topics with the estimated expenditure per year, measured in man-year units. The letter in brackets following the subject designates the place on the priority list.

TABLE 12

PLAN A - $2 MILLION/5 YEARS

First Year	Man Years	Second Year	Man Years	Third Year	Man Years	Fourth Year	Man Years	Fifth Year	Man Years
Increase collection efficience through application of additional forces (A)	3	Increase collection efficiency through application of additional forces(A)	5	Increase collection efficiency through application of additional forces(A)	4	Design,build & study a second generation scrubber(compact, employing additional forces and particle growth). (A)	6	Design, build & study a second generation scrubber (compact, employing additional forces and particle growth). (A)	6
Study various means to increase particle size (A)	3	Study various means to increase particle size (A)	3						
Study collection efficiency on back of collectors (A)	3	Study collection efficiency on back of collectors(A)	3						
		Study entrainment separation to build an efficienct compact entrainment separator(A)	4	Study entrainment separation to build an efficient compact entrainment separator (A)	6				
				Pair scrubber systems and pollution sources (A)	2	Pair scrubber systems and pollution sources (A)	2	Pair scrubber systems and pollution sources (A)	2
Compile and prepare standard methods for evaluating and reporting scrubber performance (A)	3								
Total	12		15		12		8		8

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1. A - high level priority B - medium level priority C - low level priority
2. one man year @ $35,000

TABLE 13

PLAN B - $7 MILLION/5 YEARS

First Year	Man Years	Second Year	Man Years	Third Year	Man Years	Fourth Year	Man Years	Fifth Year	Man Years
Increase collection efficiency through application of additional forces (A)	3	Increase collection efficiency through application of additional forces(A)	5	Increase collection efficiency through application of additional forces(A)	4	Design,build & study a second generation scrubber (compact, employing additional forces and particle growth)(A).	6	Design,build & study a 2nd generation scrubber (compact, employing additional forces and particle growth).(A)	6
Study various means to increase particle size (A)	3	Study various means to increase particle size (A)	3						
Study collection efficiency on back of collectors (A)	3	Study collection efficiency on back of collectors (A).	3						
		Study entrainment separation to build an efficient compact entrainment separator (A)	4	Study entrainment separation to build an efficiency compact entrainment separator (A)	6				
				Pair scrubber systems and pollution sources(A)	2	Pair scrubber systems and pollution sources (A)	2	Pair scrubber systems and pollution sources (A)	2
Compile and prepare standard methods for evaluating and reporting scrubber performance (A)	3								
		Design and build wet scrubber test facility(A)	5	Design and build wet scrubber test facility(A)	5	Design and build wet scrubber test facility(A)	4		
Study dynamic response of scrubbers (A)	4	Study dynamic response of scrubbers (A)	4			Design,build, and study scrubbers aimed at eff. simultaneous removal of contaminant (gaseous and particulate) (A)	4	Design, build, & study scrubbers aimed at eff. simultaneous removal of contaminant(gaseous and particulate)(A)	5

TABLE 13 (cont'd)

PLAN B - $7 MILLION/5 YEARS

First Year	Man Years	Second Year	Man Years	Third Year	Man Years	Fourth Year	Man Years	Fifth Year	Man Years
Mass transfer to slurries (B)	3	Obtain kinetic and equil. data for promising absorbing solutions(B)	3	Obtain kinetic and equil.data for promising absorbing solutions (B)	3				
		Design and build simple instruments for continuous measurement and control of contaminants (B)	6	Design and build simple instruments for continuous measurement and control of contaminants (B)	7	Design and build simple instruments for continuous measurement and control of contaminants (B)	7		
Study major design equations derived in Handbook and others, for agreement with available experimental data and determine limits of applicability (B)	3	Study effect of liquid phase turbulence on overall mass transfer coefficient (B)	3	Study effect of liquid phase turbulence on overall mass transfer coefficient (B)	3	Measure diffusivities for important systems (B)	3	Measure diffusivities for important systems (B)	3
				Study new construction materials (B)	3	Study new construction materials (B)	3		
Design and develop non-clogging scrubber parts(B)	3	Design and develop non-clogging scrubber parts (B)	3	Study economics of vacuum scrubbers (C)	1	Derive and test experimentally equations predicting inertial collection by various collectors for intermittent flow condition between viscous and potential (C)	2	Derive and test experimentally equations predicting inertial collection by various collectors for intermittent flow condition between viscous and potential(C)	2
Derive design equations for collection by several mechanisms acting together (C)	3			Compile information and measure surface areas in various scrubbers (C)	4	Compile information and measure surface areas in various scrubbers (C)	4		

TABLE 13 (cont'd)

PLAN B - $7 MILLION/5 YEARS

First Year	Man Years	Second Year	Man Years	Third Year	Man Years	Fourth Year	Man Years	Fifth Year	Man Years
Derive theoretically a conversion factor between hygroscopic & non-hygroscopic particles, & compare with experimental results (C)	2			Study adhesion and reentrainment of particles on various collectors (C)	2	Study adhesion and reentrainment of particles on various collectors(C)	3	Study adhesion and reentrainment of particles on various collectors(C)	5
Experimental determination of turbulent agglomeration (C)	2					Study "k_L" values for important absorbing solutions (B)	2	Study "k_L"values for important absorbing solutions (B)	4
TOTAL	32		39		40		40		27

1. A - high level priority B - Medium level priority C - Low level priority

2. one man year @ $35,000

CONCLUSIONS

With the large number of specific objectives involved in this program, it would be cumbersome to list detailed conclusions regarding each one. What we can do briefly is to give an overall sense of what was accomplished under each major heading of the scope of work. However, there is some changing of organization because each task required the use of information gained in other aspects of the program. For example, determining the adequacy of engineering design methods required the use of information also gathered under evaluation of existing systems and the investigation of usage problems. Consequently, there is some overlap among the five tasks in the scope of work and we have exercised editorial judgment in deciding where to report some specific items.

The following material is organized in the same order as the scope of work.

EVALUATION OF CURRENT TECHNOLOGY

In this section of the program we are mainly concerned with determining the adequacy of engineering design methods. It is convenient to evaluate separately wet scrubber technology as applied to mass transfer, particulate collection and a combination of both. Because these three scrubber applications differ in historical backgrounds, degrees of sophistication in theoretical development, hardware complexity, and areas of usage, they have reached different stages of development.

Mass Transfer

Scrubbers, or absorption towers, have been used for many years, mainly in the chemical industry. Methods for their analysis and design are quite complete and are usually straightforward if mass transfer coefficients are available and if no chemical reaction is involved. Three major theories have been advanced for the analysis of mass transfer operations and they have been found satisfactory for a wide variety of cases. Very good books are available and much reliable experimental data can be found in the literature.

When a reactive or absorptive slurry is used, or when a chemical reaction takes place between the absorbed gas and the scrubbing liquid, the analysis is more complicated. Models and design methods are available for these cases too. However, when the reaction is of a high order, or when the flows of the liquid and the gas are complicated, it is advisable to determine the transfer efficiency experimentally. Improved design methods for the complex cases require a better understanding of the phenomena occurring in the absorption column.

General data are abundantly available in the literature on mass transfer. Additional information is needed for the more sophisticated systems which are being considered now for the removal of SO_x and NO_x from flue gases. Basic knowledge of such reaction rates, kinetic models and equilibrium constants are also lacking for many reacting systems. In other cases diffusivities, solubilities and precipitation rates are missing. There is a need for better understanding of the flow characteristics, turbulence and the combined effects of hydro- and aerodynamics for specific designs.

Cost information is available from three sources; chemical engineering cost data, scrubber cost data, and detailed cost calculations based on component and labor costs. Except for unusual designs and exotic materials which might be difficult to estimate, cost can be obtained for all scrubber designs with about the same accuracy as for chemical process equipment.

Particulate Collection

Scrubbers for particulate removal have a shorter history of widespread use than scrubbers for mass transfer, and mainly employ inertia rather than a diffusion mechanism for the removal of the particles from the gas stream. These differences may be the reason that among engineers in practice there is little general understanding of the basic physical phenomena involved in particle removal.

Many equations and charts for the design or selection of scrubbers can be found in the literature, but they all apply to one device and a specific range of operating conditions. Most scrubber manufacturers and designers use empirical graphs - usually of the power law type - to design or select equipment. We did not find a unified approach to all scrubber designs similar to the unit mechanism approach or a selection method such as the performance and separation cut size approach that we presented in the Scrubber Handbook. Neither did we discern evidence of any superior or reliable proprietary method of design in the cases of scrubber installations reported to our survey of scrubber users.

Optimum use of the best available technology in the form of scrubber equipment requires the ability to describe quantitatively the performance potential of that equipment. If one can predict the collection efficiency and gas handling capacity of a scrubber more accurately, he can achieve lower pollutant emissions with the least amount of overdesign, and therefore, at the lowest cost. This engineering capability is so vital to the pollution control effort that we can not be content to merely report the existing fragments of empirical and theoretical scrubber design, but must take the initiative in applying the best available basic engineering knowledge to the specific cases of scrubber design.

The general approach we have taken is to seek the soundest, most generally applicable relationships which truly represent the essential mechanisms of particle collection and gas absorption. Where gaps existed we filled them as well as possible with new or improved design methods.

Because so many of the design equations presented in the Scrubber Handbook are new and so few experimental studies were available, it would be most profitable to collect more data to test the equations and perhaps lead to revisions and extensions.

Cost estimates for particulate scrubbers are somewhat less predictable than for gas absorbers because of the arbitrary pricing which is possible for some proprietary designs. We have cross-checked the available cost data from several sources and from independent calculations based on material and fabrication costs. The net result is that particulate scrubber system costs can be estimated with useful accuracy for preliminary designs and will be more accurate when one obtains actual quotations for detailed designs and specifications. This is the normal state of affairs in the field of process plant design.

Combined Collection

One of the wet scrubber's strong points is its ability for simultaneous removal of gaseous and particulate contaminants from a gas stream. However, there is a certain incompatibility since for particles $\gtrsim 1$ μm in diameter the major collection mechanism is inertial, which increases with increased gas velocities and smaller residence time, while mass transfer is favored at low gas velocities and high residence time. With the increasing need for simultaneous control of particulate and gaseous contaminants, more and more engineers are viewing wet scrubbers as the optimal means of control.

We did not find in the literature, and did not include in the Scrubber Handbook, any special design methods for a combined collection scrubber as such. However, there is generally no difficulty in calculating separately removal efficiency for particles and for gases, since there is practically no influence of one on the other. This method of approach is adequate for the design of combined scrubbers except for situations in which trace impurity buildup may influence mass transfer, which must be studied as special cases.

In the last few years since the control of power plant pollution became important, more and more data are being published on the simultaneous removal of SO_x and particulates. Because of the large magnitude of the problem and the economic aspects of SO_x removal, we expect that more data will become available in the near future. It seems also probable that new designs and new processes will be invented to solve the power plant and other related problems.

The present combined scrubbers are of the same design as the particulate and gaseous removal scrubbers, and the same cost information can serve both. However, the combined scrubber processes are getting to be increasingly complicated, and this is where more cost information is required.

EXISTING SCRUBBER SYSTEM EVALUATIONS

Many types of scrubbers are available in the market and many more designs can be found in the patent office archives. All scrubbers were classified in ten groups based on their major gas cleaning mechanisms. The results of the users survey are given in Chapter 7 of the Scrubber Handbook as tables of scrubber group vs. process or industry where these scrubbers are being used.

The scrubbers used for mass transfer are those which permit long residence time and large contact area. Among these are: plate scrubbers, packed columns, fiber beds, preformed sprays and mobile bed scrubbers.

Efficiency of a mass transfer scrubber depends mainly on the equilibrium relationship between the absorbed gas and the absorbing liquor, the absorbing area and the residence time. Design equations are presented in Chapter 5 of the Handbook. By increasing column height, any desired removal efficiency can be achieved. The choice of scrubber depends upon economic factors, absorption products, presence of other contaminant in the gas, tradition, operating conditions, and materials of construction. Efficiency can be increased by an immediate removal of the absorbent from the absorbing liquid through chemical reaction or adsorption in a slurry.

Absorption and adsorption are the two ways for the removal of one component from a gaseous mixture. The choice of the system depends mainly on economic considerations and on the specific requirements of the process involved. In many cases, the absorbed product is returned to the process or is sold. Scrubbers have the advantage of requiring the movement of only fluid streams, of being capable of continuous operation, and of requiring no moving parts (for most designs).

Inherent weaknesses of the mass transfer scrubber are the requirement for a suitable liquid and for treatment of the liquid waste. Liquid treatment is especially costly when large quantities of gas are being cleaned. Since most scrubbed gases are either acidic or basic, and in many cases they are hot, corrosion is usually a problem and costly materials of construction are required. Plugging, the need for better liquid distribution, and more intimate contact between the liquid and the gas are problems one faces with scrubbers. Carry-over of entrained scrubbing liquid can also be a major problem if a suitable entrainment separator is not available.

Particulate Collection

Manufacturers of scrubbers showed no reluctance to provide information describing the kind(s) of equipment they sell, and it is clear from the results of our survey that a great variety of scrubbers are available. Learning what these scrubbers are capable of is a more difficult task if one requires more proof than a simple assertion. It is reasonably certain that for particle separation good efficiency can be attained on particle diameters down to around 1.0 μm by the inertial mechanism.

Of the ten scrubber groups, the following are used extensively in particulate removal: plate column, preformed spray scrubbers, gas atomized spray scrubbers, centrifugal scrubbers, impingement and entrainment scrubbers, mechanically aided and moving bed scrubbers. The choice of the appropriate scrubber depends upon particulate load, size distribution and physical properties. While low velocity, low pressure drop scrubbers are adequate for relatively large particles, high velocity scrubbers are required for the removal of the one micron range particles. Particles smaller than 0.1 μm in diameter are collected in diffusion controlled scrubbers.

Particles are usually collected by one of three mechanisms: diffusion, interception, or impaction. Since diffisivity of particles larger than ≈0.1 μm is minimal, and inertia of particles smaller than ≈1 μm is small, one always finds that collection efficiency decreases with the particle impaction parameter to a minimum at about 0.2-0.5 μm, and then starts increasing as diffusion takes over. Chapters 4 and 5 of the Scrubber Handbook present general and specific collection efficiency equations for each type of scrubber.

Except for research results, useful scrubber data are almost unavailable. There are several reasons for this:

A. Scrubber users and control agencies are interested in outlet concentration almost exclusively, and do not measure inlet concentration and scrubber efficiency.

B. Scrubber manufacturers usually keep the data as proprietary information since in many cases this is the advantage they have over their competitors.

C. Determination of particle size distribution is difficult, expensive and sometimes practically impossible. Gathering of meaningful data requires a high degree of competence.

D. Scrubber users are reluctant to release information because of possible repercussions from air pollution regulatory agencies.

Of the three groups of particle collecting equipment presently employed, namely wet scrubbers, electrostatic precipitators and fabric filters, scrubbers usually have the lowest capital costs. They are simple, are not explosion prone, take less floor space, and do not require conditioning of gases and particulates. They also provide a continuous means for removal of collected material from the device. For relatively large particles, scrubbers and settling chambers are the only economic collectors.

Wet scrubbers' main weakness is high operating costs and low collection efficiency for fine particles (0.1-2μm). They are prone to clogging, corrosion and erosion, and require treatment of the collection liquor before disposal. In some cases the gas cooling and the increase in gas volume due to water evaporation are objectionable.

The gathering of reliable inlet and outlet particle size distribution is essential to the development and substantiation of good scrubber design models and equations.

Combined Mass Transfer and Particulate Collection

Since scrubbers for combined collection are undergoing fast development now, it is difficult to list the groups which are used. The types being tried are: moving beds, gas atomized sprays, and combinations of several groups, such as a venturi followed by a packed bed. Performance is the same as for particles with regard to the particulate matter and the same as for the mass transfer for the gaseous part. The incompatibility of inertia and diffusion mechanism is the main weakness of combined scrubbers. One requires long residence time, and the other short.

SCRUBBER USE AND PROBLEMS

Scrubbers are used to control emissions from many diversified sources. Table 14 shows the distribution of scrubber groups as employed by various industries. The table representing 294 scrubbers was compiled from the information collected through the users survey.

TABLE 14

PROCESSES TO WHICH EACH TYPE OF SCRUBBER IS APPLIED+

	Plate	Packed Bed	Fiber Bed	Spray	Venturi	Centri-Fugal	Baffle	Impg.& Entr.	Mech. Aided	Moving Bed
Calcining	(1) 6	(1) 2	(0) -	(5) 13	(23) 21	(0) -	(0) -	(3) 43	(0) -	(0) -
Combustion	(3) 17	(0) -	(0) -	(2) 5	(2) 2	(1) 2	(0) -	(2) 29	(0) -	(2) 9
Crushing	(1) 6	(0) -	(0) -	(0) -	(0) -	(11) 26	(0) -	(1) 14	(0) -	(1) 5
Drying	(7) 39	(0) -	(0) -	(4) 10	(19) 18	(30) 70	(1) 100	(0) -	(1) 25	(14) 64
Gases	(3) 17	(33) 72	(2) 40	(18) 45	(10) 9	(1) 2	(0) -	(1) 14	(2) 50	(1) 5
Liquid Mists	(0) 0	(11) 24	(3) 60	(3) 7	(0) -	(0) -	(0) -	(0) -	(0) -	(0) -
Smelting	(3) 17	(1) 2	(0) -	(8) 20	(54) 50	(0) -	(0) -	(0) -	(1) 25	(4) 18

+ Read vertically. Example: 39% of all plate type scrubbers are applied to controlling drying processes.

Numbers in parentheses refer to number of scrubbers reporting the information to the scrubber study.

The use of available knowledge in the design and specification of scrubbers is not as effective as one would hope. Many installations are built on the basis of some vague notions about what is being emitted and how well the scrubber will be able to cope with it. There is a tendency to have the most confidence in what has been used supposedly successfully before. The not very practical result of this variety of "practical approach" has been that many systems have not operated up to expectations and had to be modified or even replaced.

Particle size distributions were unavailable for the majority of the scrubbers we surveyed. In some cases even concentrations were not known. This is due in part to the usual preoccupation with outlet loading only, in part to the belief that it is unnecessary to have specific data, and in part to the inability to make the measurements. There is also a tendency to forget about the scrubber once it has passed inspection. Consequently it is very rare that the continuing performance of a scrubber is measured.

Auxiliaries are usually not much of a problem but there are cases where blowers have been a source of great difficulty. Unbalancing of blower wheels due to either dust accumulation or corrosion is one of the common problems. These same causes, dust buildup, errosion and corrosion, can also be responsible for failures of other components such as entrainment separators, flow straighteners, support plates, etc. Better knowledge of suitable materials has a great potential for cost savings.

Liquid treatment and/or waste disposal can present difficulties in some cases. Engineering knowledge and skill are important to the economical resolution of these. There is an area of uncertainty in the prediction of how much cleanup of the recycle liquid is necessary to prevent plugging and erosion problems.

All-in-all, scrubbers have been used successfully in thousands of installations and will be used increasingly in the future. They possess unique capabilities as well as limitations. Given that they are properly applied, they can be designed with as much confidence and success as any other type of air pollution control equipment.

New Applications

Scrubbers account for about 22% of the air pollution control equipment sales in 1971, scrubber sale projections indicate that scrubbers will about equal electrostatic precipitators in 1976, and will account for about 26% of overall sales.

Despite this large market, there are many situations in which scrubbers are not used or are little used, and the question comes to mind; whether this is as it should be. The choice of any air pollution control devices requires that the performance be adequate, the system fit within any other constraints, and that investment and operation costs be suitable. There are many instances in which the correct decision was not made. Sometimes the problem itself is not properly defined, the control device performance and cost characteristics were not known, or a suitable alternative was not considered.

Conditions under which new or increased application is possible are as follows:

1. Performance requirements change so that alternatives should be re-evaluated.

2. Scrubbers have improved since the decision to use another type of control equipment has been made.

3. Scrubber systems become relatively cheaper.

4. Accessory problems can now be solved satisfactorily.

5. Scrubbers never were as bad as people may have been told.

6. The person selecting a system simply never thought of using a scrubber.

Changing technology and emission regulations may lead to the future application of scrubbers to pollution control problems where scrubbers are not widely applied now. The most promising areas are for the cleanup of submicron particles and for inorganic gases. Additional scrubber applications for the removal of submicron particles will require the development of scrubbers capable of removing these particles with good efficiency without developing the high operating costs (due to high energy consumption) presently needed. Tightened and enforced regulations on the emissions of inorganic gases will require increased use of scrubbers for gas scrubbing.

Some specific industrial applications where increased scrubber use seems indicated are:

1. Power plants burning coal, oil, or wood.
2. Rock products plants such as cement, alumina, lime, bauxite, and magnesium oxide.
3. Steel plants for open hearth, ore roasters, taconite and hot scarfing.

4. Mining and metallurgical plants, including: zinc roaster, copper roaster, copper reverberatory, ilmenite, titania and molybdenum.
5. Refinery catalyst.
6. Coal cleaning and drying.
7. Feed and flour mills.

Recommendations for R & D

A recommended Research and Development Plan has been prepared aimed at increasing scrubber use by overcoming the scrubber limitations and shortcomings discussed earlier. Two criteria have been used in assigning priorities to various research topics. The first one is that pressing air pollution problems have first priority, and the second is that scrubbers should be applied primarily in their areas of strength.

Several approaches can lead to increasing the collection efficiency of scrubbers in the fine particle range. One is to apply additional collection mechanisms, preferably those which are independent of particle size. Such mechanisms involve the use of flux forces, such as diffusiophoresis and thermophoresis. Another mechanism is the increased collection of small particles by the back of spheres at high Reynolds numbers. A different approach to the same problem would be to grow the particles to sizes which can be collected readily. This can be achieved through agglomeration, condensation or chemical reaction.

In the mass transfer area, better and more economical processes are needed. This requires the study of more complex systems such as mass transfer to slurries, a search for reacting or absorbing chemicals that can be regenerated and returned to the system and a study of the effect of liquid phase turbulence on the mass transfer coefficients.

A wide range of work is still needed to establish reliable design methods. The research plan lists a number of projects that should be undertaken to make the available equations more accurate, to develop new equations where none are now available, and to gather extensive experimental coefficients and data to support any design.

Much of the research plan is aimed at developing the second generation scrubber. This scrubber should be designed from the start to be a pollution control device, possibly for a definite application, rather than an adaptation from the existing chemical engineering state of the art. Flux forces, agglomeration and condensation, either in combination or separate, can overcome the fine particle problem. A new efficient and compact entrainment separator would help in reducing the scrubber size, cost and emission rate. An effort will be made to reduce waste liquid treatment costs, whether through recycle, regeneration or more sophisticated treatment methods. After all this is accomplished, the new scrubber generation will capture a larger portion of the air pollution market.

The last part of the research plan looks at the scrubber from the air pollution control authority point of view. To meet emission criteria constantly and not only during the initial test, pollutant monitoring equipment and knowledge of the dynamic behavior of the scrubber are required.

Based on the criteria mentioned earlier, the list of research topics has been arranged in two five-year research plans. One is a two million dollar research plan, and the second is a 7 million dollar plan. Both plans list the various research topics with the estimated expenditure per year, measured in man-year units and their place on the priority list.

APPENDICES

Appendix A - Letter to Scrubber Manufacturers

Appendix B - Brief Description of "Wet Scrubber System Study"

Appendix C - Letter to Scrubber Users

Appendix D - Scrubber Questionnaire - Long Form

Appendix E - Scrubber Questionnaire - Short Form

APPENDIX A

Ambient Purification Technology, Inc.

P O BOX 71
RIVERSIDE
CA 92502
(714) 682-6211

November 17, 1970

Dear Sir:

We are engaged in a study of Wet Scrubber Systems for gas absorption and particle removal under a contract from the National Air Pollution Control Administration, as the enclosed sheet describes.

An important part of the study is the survey of wet scrubbers currently available. To insure the completeness of our survey, would you please send us information describing the scrubbers you make. We would especially appreciate data on scrubber costs, and any specific case studies you could provide.

Thank you very much.

Yours truly,

DAVID LEITH
Engineer

DL:lm

encl.

Ambient Purification Technology, Inc.

Air & Water Purification
P.O. BOX 71, RIVERSIDE, CA. 92502

APPENDIX B

Brief Description of "WET SCRUBBER SYSTEM STUDY"

Ambient Purification Technology, Inc. has contracted with the Air Pollution Control Office of the Environmental Protection Agency (formerly the National Air Pollution Control Administration) to perform a "Wet Scrubber System Study", Contract No. CPA 70-95.

The general scope of work is to: (1) review and assess the status of wet scrubber technology; (2) prepare a critical review and evaluation of existing scrubber systems and define current practices in the application of scrubbers for air pollution control; (3) define usage problems and the research and development needed to improve the performance of scrubbers as now applied; (4) identify potential new applications of wet scrubbers to additional air pollution control problems, and (5) develop specific research recommendations.

The final results of this contract will include a research program plan and a handbook on wet scrubbers. The handbook will be completed in the fall of 1971 and should be available to the public shortly after.

APPENDIX C

Ambient Purification Technology, Inc.

APT

P O BOX 71
RIVERSIDE
CA 92502
(714) 682-6211

We have contracted with the National Air Pollution Control Administration to perform a study of wet scrubber systems for gas absorption and particle collection. A sheet describing the study is enclosed.

As part of the study, we are gathering information on the performance of various types of scrubbers on the job. We hope to determine the types of scrubbers most applicable to each industrial process, and point out scrubber strengths and weaknesses so that better, less expensive systems can be developed. Results will be published in a handbook which will be available to you.

We would appreciate your indicating a willingness to participate in the study by filling out and mailing the enclosed postcard. Your company name will not be mentioned if this is your preference.

Sincerely yours,

David Leith
Engineer

DL:lm

encls: postcard
description

Air & Water Purification

Ambient Purification Technology, Inc. P.O. BOX 71, RIVERSIDE, CA. 92502

APPENDIX D

B.O.B. #OMB 85-S 70033
Expires 12/31/71

"WET SCRUBBER SYSTEMS SURVEY OF USE AND PERFORMANCE"

Section I. COMPANY IDENTIFICATION Date: ____________

1. Name & location of company:
   a. Name: ____________
   b. No., Street: ____________
   c. City: ____________ State: ____________ Zip Code: ______
2. Location of plant if different from above:
   a. Plant/Division: ____________
   b. No., Street: ____________
   c. City: ____________ State: ____________ Zip Code: ______
3. Person to contact regarding information contained in this report:
   a. Name: ____________
   b. Department/Division: ____________
   c. Telephone: (Area code) ____________
4. Principal products manufactured at this plant: ____________

____

Standard Industrial Classification, if known: ____________

Note:

This survey of wet scrubber systems is being performed for the National Air Pollution Control Administration. It will point out the strengths and weaknesses of scrubbers so that better, less expensive systems can be developed. A "Scrubber Handbook" will be written and will be available to you.

Your participation will be helpful even if you can only provide a small part of the information requested, or if you must estimate quantities. Please fill out a separate copy of pages 2, 3 and 4 for each scrubber application. Either make additional copies or write us for more, whichever is most convenient for you.

If you have any questions, please call us collect at: (714) 682-6211.

APPENDIX D (CONT'D)

"WET SCRUBBER SYSTEMS SURVEY OF USE AND PERFORMANCE"

Scrubber name and type:____________________

(Please indicate units when numerical replies are provided, for example: pounds per hour; tons per day.)

1. a. Process operation

   b. Pollutant recovered

   c. Process Type (circle one) Continuous/Batch/Batch(timing___)

2. a. Process capacity____________________

   __________(/hour) Scrubber feed temperature__________

   b. Pollutant concentration________,weight per hour__________,

   particle size or distribution____________________

3. Approximate costs: Scrubber__________; Fans & duct______;

   Auxiliaries________; Total__________Date installed________

4. Collection efficiency__________How determined?__________

5. Please indicate:

   a. Any major difficulties with your system:__________

   ____

   % on stream time:__________No. of failures/year:__________

   b. What aspects of performance or operation could be improved, based on your field experience:__________

   ____

   ____

   c. Suggestions for improvements in design or manufacture:______

   ____

   d. Research suggestions:____________________

   ____

   e. Please estimate accuracy of data__________

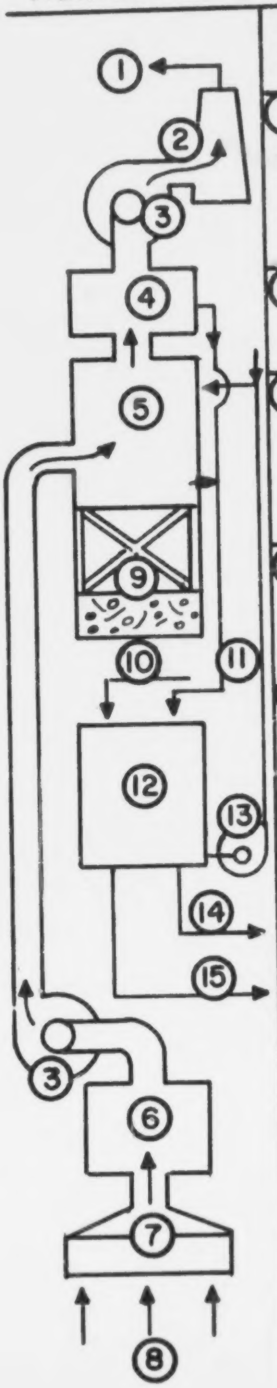
   ____

WET SCRUBBER SYSTEMS STUDY

Date __________

Company __________ Scrubber __________

Address __________ Respondent __________



ITEM DESCRIPTION—Such as; Name, Model, Size, Capacity, Flow Rate, Temperature, Cost.	COMMENTS Such as; Performance, Material of Construction, Reliability, Corrosion.
① GAS OUT (^S_ACFM) Temp. (°F) Comp. Contaminant (gr./^S_ACF) (lb/hr.)	Particle Dia. (Micron)
② DUCT + STACK Cost.Purch. $ Inst. $	Mtl. Constr.
③ FAN (Push or Pull) HP Mfg. Model Capacity (^S_ACFM) "W.G. Purch. $ Inst. $	Mtl.
④ ENTRAINMENT SEPARATOR Purch. $ Inst. $	Mtl.
⑤ SCRUBBER Mfg. Model Size (ft) Cap. (^S_ACFM) Description Purch. $ Inst. $	Mtl. Corrosion Rate Any Changes Req'd.? Temp. In Temp. Out
⑥ GAS PRE-TREATMENT Purch. $ Inst. $	
⑦ HOOD + DUCT Purch. $ Inst. $	Mtl.
⑧ GAS IN (^S_ACFM) Temp. (°F) Comp. Contaminant gr./^S_ACF (lb/hr.)	Source

WET SCRUBBER SYSTEMS STUDY

Date ________

Company ________ Scrubber ________

ITEM DESCRIPTION	COMMENTS
⑨ SUPPORTS + FOUNDATION Purch. $ Inst. $	
⑩ CHEMICALS Name Quant. Cost ($/mo.)	
⑪ LIQUID PIPING Contaminant ppm. Purch. $ Inst. $	Cap. (GPM)
⑫ LIQUID TREATMENT Cap. (gal.) Method* Equip. Changes Req'd? Purch. $ Inst. $	Mtl.
⑬ PUMP Contaminant ppm. Cap. (GPM) Make Up (GPM) Head (ft.)(psi.) Purch. $ Inst. $	Mtl.
⑭ LIQUID WASTE Contaminant ppm. Cap. (GPM) Cost ($/mo.)	Disposal Method
⑮ SOLID WASTE % Water Cap. ton/mo. Cost ($/mo.)	Disposal Method
⑯ POWER Equip. Cost ($) Op. Cost ($/mo.)	⑰ WATER Equip. Cost ($) Op. Cost ($/mo.)
⑱ OP. LABOR ($/mo.) (Man-Hr./mo.)	⑲ MAINTENANCE Mtls. $ ($/mo.) (Man-Hr./mo.)

OTHER NOTES (please number)

* Draw flowsheet on back, detailing equipment, capacity and manufacturer.

SCRUBBER OPERATION DATA

NUMBER	Example		
CATEGORY	coal drier		
process name	fluid bed drier		
SCRUBBER: name	venturi (2)		
type	—		
packing, if appl.	—		
size	2 venturis, each with a 2 ft. dia. throat		
mat'ls of const.	316 S.S.		
CARRIER GAS: name	drier gas		
composition	—		
temp., °C	— °C in/ 150°F ~~°C~~ out	°C in/ °C out	°C in/ °C out
humidity, Tsat., °C	—		
flow rate, m^3/hr	100,000 cfm		
CONTAMINANTS: particle name	coal dust		
particle density, g/cm^3	—		
" size, microns	50% under 5 /16% under 1 (1)	50% under /16% under	50% under /16% under
" loading g/m^3	5 grams/ft^3 (1) in/ 0.05 grains/ft^3 out	in/ out	in/ out
gas, name	—		
" ppm	— ppm in /— ppm out	ppm in /ppm out	ppm in /ppm out
SCRUBBING SOLUTION: name	water		
total flow rate, m^3/hr	500 gpm (2)		
composition	—		
pH	— pH in /— pH out	pH in /pH out	pH in /pH out
makeup, m^3/hr	20 gpm		
EFFICIENCY: particles	99%		
gas	—		
COSTS: Δ P, cm of H_2O	40" W.G.		
installed cost, $	$ 200,000		
operating cost, $/mo			
COMMENTS: including maintenance problems, health and safety problems, waste disposal, suggestions for future, etc.	(1) outlet from cyclone precleaner (2) reused in washing plant		

WET SCRUBBER SYSTEM STUDY VOLUME II

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Jhuda Goldshmid
David Leith
Dilip Mehta

Prepared for

CONTROL SYSTEMS DIVISION
OFFICE OF AIR PROGRAMS - ENVIRONMENTAL PROTECTION AGENCY

CONTRACT NO. CPA-70-95

A.P.T., INC.

(Ambient Purification Technology)
P. O. Box 71, Riverside, California 92502

July, 1972

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I

INTRODUCTION

A search of the literature was made as part of the Wet Scrubber Systems Study for information on the design and application of wet scrubbers. The purpose was to find all theoretical, experimental, and practical work on wet scrubbers which has been reported.

Abstracting services were utilized. Computer printouts of relevant literature references were received from APTIC, NTIS, AEC, NASA, and Midwest Research Institute. Chemical Abstracts, Air Pollution Abstracts, and British Chemical Engineering Abstracts were consulted.

A direct manual search of forty-eight technical journals carrying articles pertinent to scrubber systems was carried out. Twenty-five journals were searched from 1950 to present. Library facilities at UCLA, California Institute of Technology, and University of California at Riverside were used.

Most of the evaluation of literature came at the time the literature was initially screened. If an article was judged as contributing to the knowledge of scrubbers, it was noted and acquired. If there was doubt as to the contribution of an article to scrubber understanding, it was also noted and acquired. It was deemed prudent to select all articles which might be of use, rather than to be overly selective at the outset and reject these articles. Of the thousands of literature articles reviewed, about 2,000 were judged pertinent, were acquired, classified, and filed in the APT library.

Many of the references found are cited as references in the Wet Scrubber Handbook. However, other references which are not cited, may be of use. The Wet Scrubber Bibliography contains all references cited in the Wet Scrubber Handbook, plus the additional references found in the literature search, but not cited in the Handbook. The Handbook cites about 750 references; the Bibliography about 1,700.

The Wet Scrubber Bibliography is organized in a manner parallel to that used in the Wet Scrubber Handbook. Each section in the Wet Scrubber Handbook with references has a corresponding section in the Bibliography with the same number and title. For example, Section 4.6 in the Handbook, "Unit Mechanisms for Particle Separation", has a corresponding Section 4.6 in the Bibliography with the same title. All references cited in the Bibliography are pertinent to the subject matter in the corresponding Handbook section. If a reference is pertinent to more than one Handbook section, its Bibliography listing is duplicated. Within each section of the Bibliography the organization of references is alphabetical by author.

By organizing the Bibliography in a manner parallel to that used in the Handbook, it is hoped that the references listed here will be of most use in supplementing Handbook material. Note that not all sections in the Handbook have corresponding sections in the Bibliography. This is because some Handbook sections are introductory, organizational, or descriptive in nature, and do not have pertinent references. For this reason, the Bibliography starts with Section 4.2, "Basic Principles: Mass Transfer", rather than with Section 1.0, "Introduction".

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